TECHNICAL BULLETIN No. 247 AUGUST, 1931

FOREST TYPES IN THE SOUTHWEST AS DETERMINED BY CLIMATE AND SOIL

BY

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Forest Service

UNITED STATES DEPARTMENT OF AGRICULTURE, WASHINGTON, D. C.

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CONTENTS

INTRODUCTION

No other form of agriculture is so completely subject to the forces of nature as is the growing of timber crops. Trees may not be more sensitive to changes in their environment than are other forms of vegetation, but their long span of life calls for greater constancy of favorable conditions than is required by plants which mature and reproduce in one or a few years. In only a very limited way is it possible for man to modify these forces, and therefore the forester, to be successful, must understand and learn to work in harmony with them.

[1] The Southwestern Forest and Range Experiment Station is maintained in cooperation with the University of Arizona. The investigation here reported has been confined almost entirely to Arizona and New Mexico. Although these two States do not comprise the entire region generally included in the more or less vaguely defined Southwest, they do constitute the major and most typical part as far as the forestry is concerned.

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The observation that certain tree species and types of forest are associated with certain types of climate and soil is older than forestry itself, for long before forestry was practiced biologists had learned to recognize forest trees as indicators of climatic zones. As for the forester, nothing could be a more quickening challenge to his research instinct than the question of why one tree species makes its home on the mountain tops, another in the valleys, and another on intermediate slopes. Such questions were among the first to engage the attention of research workers at Forest Service experiment stations. Studies of climatic zones in relation to the natural occurrence of forests have been made by Bates (*2*)[2] in Colorado, and by other workers[3] in Idaho, Montana, Utah, and California; also by the writer (*32*) in Arizona as a preliminary to the present bulletin. Among other contributions in the same general field but dealing less specifically with forest trees are the works of Merriam (*29*), Clements (*12*, *13*), Clements and Weaver (*14*), Sampson (*38*), Shreve (*41*), and Livingston and Shreve (*26*).

Although progress has been made in the correlation of vegetation and physical conditions, much remains to be done. Forest meteorology in this country is still in its infancy. Soil surveys such as are made in agricultural sections are not adapted to forest lands. Furthermore, even if soil and meteorological data were available, neither foresters nor other plant investigators are in a position to know how to apply them effectively. Our knowledge concerning the reactions of plants to changes in heat, light, and moisture is inadequate. Too little distinction is made between air temperature and plant temperature and between air temperature and insolation. "Light" in the forest may be more a phenomenon of heat than of illumination. Moisture effects are more readily perceived than are those of heat and light, but under natural conditions the three are so intimately related that confusion is avoided with difficulty. Properly conducted experiments would do much to clarify our conceptions of these important subjects.

The object of this investigation has been further advancement toward an understanding of the biological relations between forests and their environment. More specifically, the object has been to ascertain under what conditions different kinds of forests do or do not occur, and in this way obtain an expression of their requirements. In such a study, the first step is to obtain a measure of the physical conditions prevailing in each type of forest. If it is found, as has in fact proved to be the case, that a given forest association represents rather definite conditions of climate and soil, a knowledge of these relationships is of obvious value. Having this in mind, the writer has presented the available records of physical factors with a view to serving forest management and future research as well as the immediate purpose of this investigation. The correlation between forests and physical conditions should not only designate the critical factors but also express them in quantitative terms. It should go a step further and state the range of optimum and possible conditions for each species. The present investigation has not been carried far enough to treat this phase in a final manner, but such available figures as seem justified will be presented.

[2] Italic figures in parentheses refer to Literature Cited, p. 141.
[3] The results of these studies are not yet published.

Although soil as a factor in the demarcation of forest types probably deserves more attention than it has received, it is in this region overshadowed by climate. Besides exerting greater direct influences upon vegetation, climate, as will be shown later, determines to a large extent the character of the soil.[4]

THE FOREST TYPES [5] OR ZONES AND OTHER VEGETATIONAL ZONES OF ARIZONA AND NEW MEXICO

Altitude far more than latitude determines the character of climate and vegetation in the Southwest. Altitudes range from less than 100 feet in southwestern Arizona to about 13,000 feet in northern Arizona and northern New Mexico. Forests occur mainly above the 5,000-foot contour, the lower limit depending somewhat

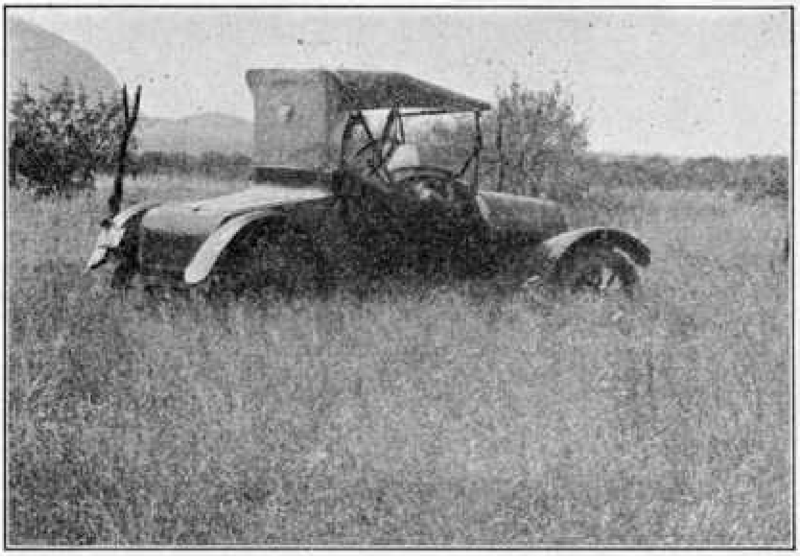

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FIGURE 1.—Luxuriant growth of grama grass (*Bouteloua rothrockii*) on a protected area in the so-called desert of southern Arizona. Mesquite bushes (*Prosopis velutina*) in the background

upon exposure, soil, and other local conditions. The upper limit of tree growth approximates 11,500 feet, varying with local conditions, of which exposure is the most important.

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[4] It is of interest to note that in a similar investigation by Cajander (8) in Finland, soil is regarded as the all-important factor, climate being barely mentioned. This difference may be accounted for by the fact that in Finland local climatic variations are so small as to be inconsiderable.

[5] The term "forest type," as generally understood by foresters, denotes an ecological unit characterized by uniformity in composition as to tree species. Corresponding uniformity in physical conditions is usually implied. Forest types are as a rule designated by the names of the species which predominate in the stand as, for example, western yellow pine type or Douglas fir type. Among ecologists the terms "association" or "consociation" are synonymous with forest type, consociation being restricted to units which are dominated by a single species. Thus, the western yellow pine type would be called a consociation, whereas the Douglas fir type, which usually is made up of several species, or the mixed-conifer type, would be called an association. Plant succession is recognized by the forestry profession in the use of the terms "temporary" and "permanent" forest type. "Forest influences," meaning the reaction of the trees and other vegetation upon soil, water, and atmospheric conditions, appears in the oldest forestry literature.

Four forest zones or types are commonly recognized in this region. These are, in ascending order, the woodland, western yellow pine,[6] Douglas fir, and Engelmann spruce. Below these are two non-

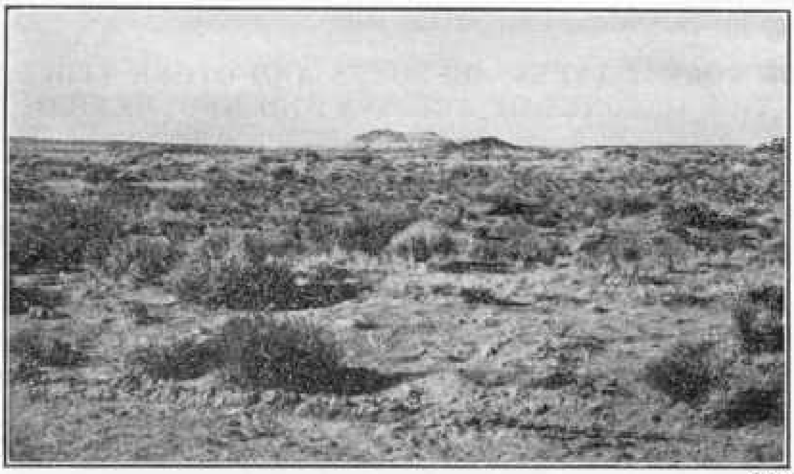

FIGURE 2.—A common shrub-grass association of the grassland formation. *Chrysothamnus* sp., *Atriplex* sp., *Gutierrezia sarothræ, Bouteloua gracilis, B. curtipendula,* and *Sporobolus airoides.* The grasses and the Atriplex have been closely grazed

forest zones which, while they are not treated in this bulletin in any detail, are sketched in roughly to complete the regional picture of plant zones. Thus, lowest of all lies what is popularly known

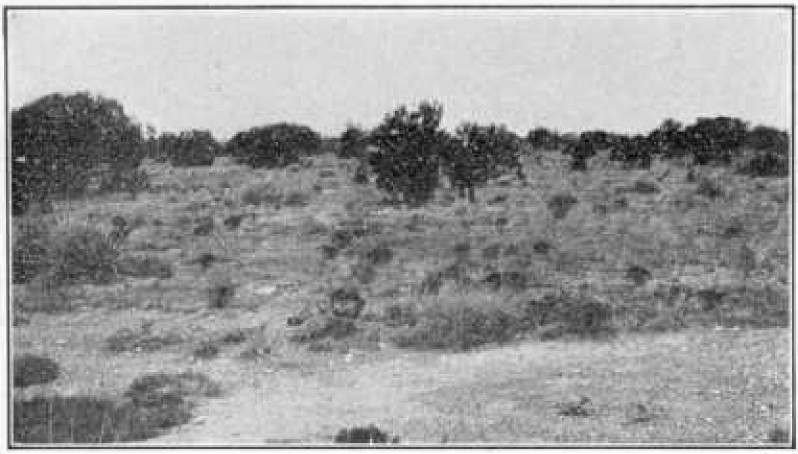

FIGURE 3.—Transition from grassland to woodland east of Flagstaff, Ariz. Altitude about 5,700 feet; grassland vegetation with a few dwarf specimens of one-seed juniper. The precipitation here is slightly more than 9 inches, and the soil is moderately shallow. The lower border of the woodland may be seen as a dark line in the distance

as the desert (fig. 1), in reality a zone very rich in plant life. Shrubs now prevail in the desert zone, although grasses were

[6] The name *Pinus scopulorum* has been applied to the Rocky Mountain form of western yellow pine occurring in this region in order to distinguish it from the more or less distinct Pacific coast form. The Forest Service, however, has officially adopted the name *P. ponderosa* for both forms, and this name will be used throughout the present bulletin.

probably abundant before the days of intensive grazing. Above the desert is the grassland zone (fig. 2), which, with the not always distinctive chaparral zone, merges into the lower margins of the woodland (fig. 3). The distinction between grassland and desert is rather arbitrary but is based upon a recognition of the obviously greater dryness prevailing below an altitude of about 3,000 feet.

The plant zones here discussed have been taken up in their natural

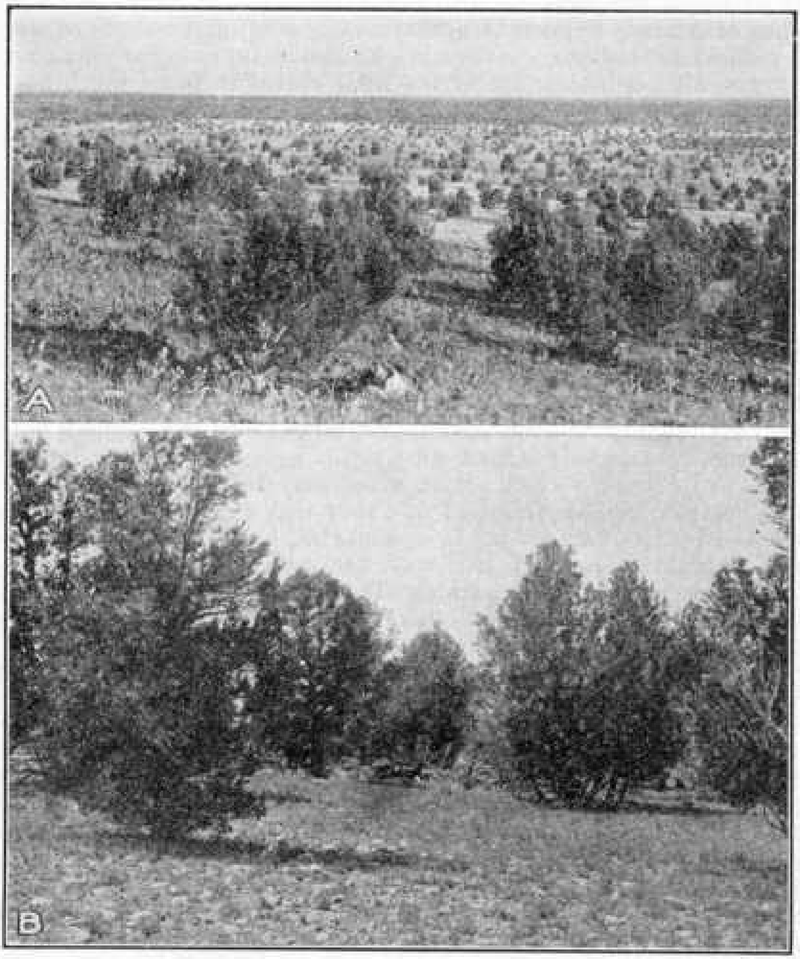

FIGURE 4.—A, *Juniperus utahensis* encroaching upon open areas. In the region south of Ash Fork, Ariz., thousands of acres of what is apparently grassland but probably in reality is burned woodland are being invaded by juniper. B, Typical piñon-juniper woodland

vertical order, indicating the approximate altitudinal limits and characteristic species of each. A general description of the woodland and timberland zones follows.

WOODLAND

Foresters use the term "woodland" to distinguish the low, spreading tree growth characteristic of this lowest of the several zones occupied by continuous bodies of trees. Two or more fairly distinct kinds of woodland, each of which may be designated as a forest type, occur in the Southwest. Of these the piñon-juniper type is most common. It is made up of several species of piñon and juniper and is rather common over the entire region between altitudinal limits of 5,000 and 7,000 feet. The evergreen-oak type, represented mainly in Arizona oak and Emory oak, is confined to the southern half of the region between altitudes of about 4,500 and 6,000 feet. Stands of Arizona cypress (*Cupressus arizonica*) and smooth cypress (*C. glabra*) in southern Arizona might also claim recognition as forest types, although they are of too little extent to be of much commercial importance.

The usually open character of the woodlands, often caused by fire, permits abundant growth of herbs and shrubs between the trees. (Fig. 4, B.) The most characteristic grass is blue grama (*Bouteloua gracilis*). Species of the grassland formation, such as side-oats grama and tobosa grass, are also more or less common. Characteristic shrubs in the piñon-juniper type are quinine bush (*Cowania mexicana*) and mountain-mahogany (*Cercocarpus montanus*). Sagebrush (*Artemisia tridentata*) is the predominant shrub within this type over large areas in northern Arizona and northern New Mexico.

Mainly because the piñon and the two most common junipers, one-seed and Utah, are very sensitive to fire, large areas of woodland have been almost completely wiped out by this agency, probably in conjunction with bark beetles. Such areas may become grasslands, or, where overgrazing has followed fire, they may grow up to brush, as suggested by Leopold (*25*). It is doubtful, however, whether typical chaparral originates in this way, because it shows many indications of being a climax formation. This view has been expressed by Calkins (*9*). If fires are kept out of woodland burns, the trees come back in time, especially within the range of Utah juniper, which is particularly aggressive as an invader of new territory. (Fig. 4, A.) Investigations by Miller (*30*) have shown that sheep, feeding on the berries, are an important agency in disseminating this juniper. Moreover, the junipers, unlike the pines, firs, and spruces, are seldom browsed. Since the seeds of all these trees are heavy, most of them fall directly under the outer edge of the crown where the seed bed is best. Here decayed leaf litter has formed a mulch on the surface of the soil, and the shade, while preventing excessive evaporation is not sufficient to suppress the seedlings. It is common for piñon and juniper seedlings to spring up in large numbers close around the old trees.

Although the woodlands produce but little saw timber and generally give good yields of farm crops only under irrigation, they are of considerable economic importance, particularly as this type clothes extensive watershed areas. They afford excellent grazing and nearly all of the tree species present are valuable for fuel. The junipers are highly prized for fence posts. In northern New Mexico the piñon is very largely used for ties and props in coal-mining operations, and in recent years the piñon-nut industry has assumed economic importance. Because in this zone the biological balance is very delicately adjusted, excessive grazing, clearing of lands, cutting, and fire, coupled with fairly heavy storms, have perhaps a greater effect than in any of the other zones in causing serious erosion.

WESTERN YELLOW PINE ZONE

Western yellow pine occurs in pure stands at altitudes ranging most commonly from 7,000 to 8,000 feet. The Arizona pine of southern Arizona is similar in appearance but is distinguishable by the fact that it has from three to five needles in a sheath whereas western yellow pine usually has only two or three. Still another species of very limited occurrence in southern Arizona is Apache pine (*Pinus apacheca*). Toward the lower limits of the type, piñon and one or more of the junipers occur in mixture with western yellow pine; toward the upper limits limber pine, Douglas fir, and white fir are common associates. Rocky Mountain white oak (*Quercus utahensis*), a distinctly subordinate species, grows with western yellow pine through a considerable portion of its range.

Like the woodlands, the western yellow pine forest, because of recurring fires which have killed the young growth from time to time, is open, permitting a great variety of herbs and shrubs to grow between the trees. Characteristic grasses are the bunch grasses (*Festuca arizonica*, *Muhlenbergia montana*, and *Blepharoneuron tricholepis*), squirreltail grass (Sitanion), wheatgrass (*Agropyron smithii*), black dropseed (*Sporobolus interruptus*), and June grass (*Koeleria cristata*). Blue grama is common in parks and in the lower edges of the western yellow pine zone, but it is not characteristic on optimum western yellow pine sites. Among the more common nongrasslike herbs are yarrow (*Achillea lanulosa*), the lupines, of which there are several species, meadow rue (*Thalictrum wrightii*), red and yellow pea (*Lotus wrightii*), vetch (*Vicia americana*), sage (*Artemisia dracunculoides* and *A. mexicana*), and loco weeds (Oxytropis), *Senecio spartioides*, and pingue (*Actinea richardsoni*). The scrub oaks (*Quercus gambelii*, *Q. undulata*, and *Q. reticulata*), mountain-mahogany, and cliffrose or quinine bush are common in the lower edge of the type.

An outstanding feature of the western yellow pine forests is the tendency of the trees to occur in even-aged groups. Within a radius of 100 feet one may find groups of veteran western yellow pines, of immature "blackjacks," of poles 6 to 8 inches in diameter, and of seedlings or saplings. (Fig. 5.) Groups above the sapling size vary from 3 or 4 trees to as many as 50. In some localities the grouping habit is less pronounced than in others, but it is everywhere noticeable. Mature trees are from 200 to 400 years old, and one specimen was found to be 640 years old, but merchantable size is attained in from 150 to 200 years. Maximum diameters are 4 to 5 feet, and heights range up to 125 feet. (Fig. 5, B.) The number of trees more than 12 inches d. b. h.[7] per acre in a virgin stand ranges from 15 to as high as 50. The volume per acre usually runs from 8,000 to 10,000 board feet, although in certain localities, notably the Sitgreaves National Forest of Arizona, yields as high as 20,000 board feet are common. It is believed that under protection against fire and grazing damage, stands of the heaviest type now found would be the rule rather than the exception.

Because of their high timber value and their accessibility, the western yellow pine forests have been heavily exploited. Unregu-

[7] D. b. h.=diameter at breast height (4.5 feet).

lated cutting followed by fire and overgrazing has resulted in nearly complete denudation of many areas. Where seed trees are left

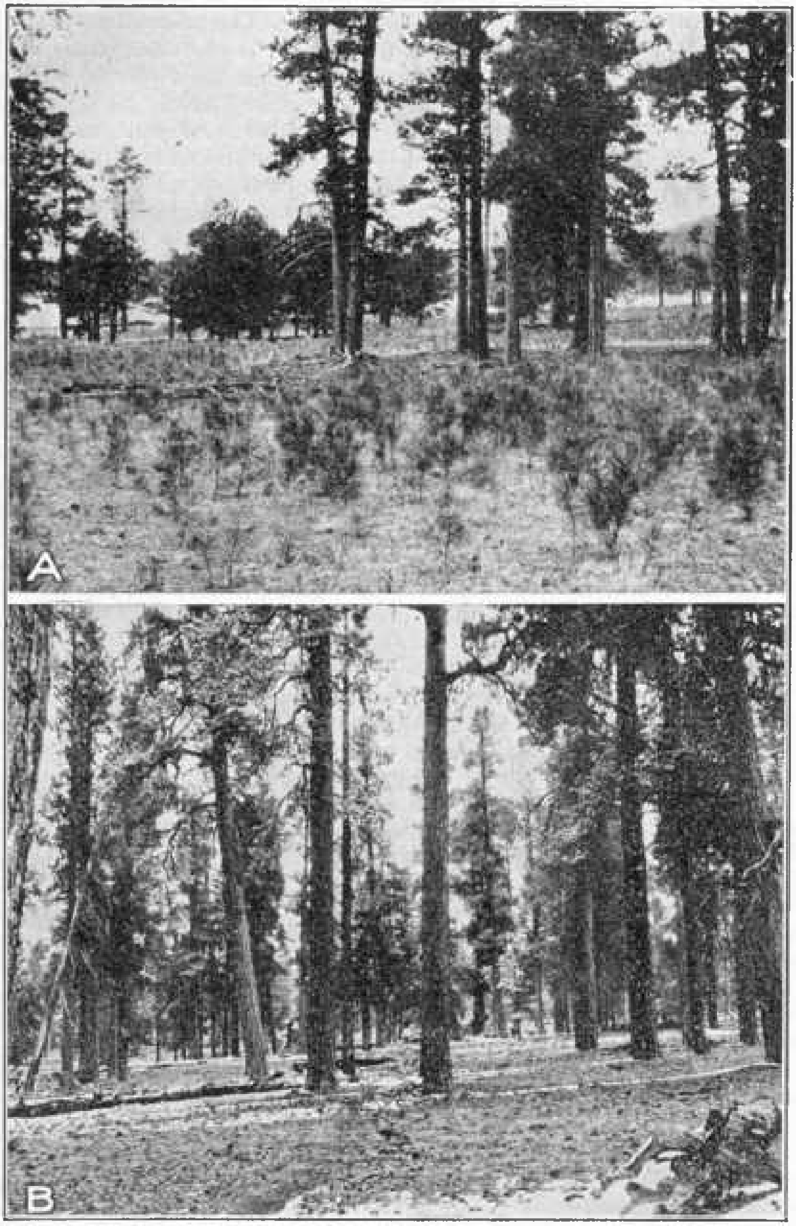

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FIGURE 5.—Typical stands of western yellow pine; A, open stand with seedlings and saplings between groups of old trees; B, dense mature stand

and young growth is protected, a perpetual stand is usually assured. Fire does not as a rule destroy mature trees unless fed by a large amount of dry material, such as slash left after cutting. Ordinary grass fires, however, destroy seedlings and saplings and result in a thinning of the mature stand by killing some of the large trees.

With the development of the forest as a timber-producing area goes its conservation as a watershed and recreational area. Although the western yellow pine stands are not dense enough to form an ideal watershed, the tree canopy, together with the leaf litter, the young tree growth, and the herbaceous vegetation, exerts an important influence in regulating run-off and checking erosion.

A considerable acreage of open or sparsely timbered land within the western yellow pine zone has been brought under cultivation. Under the most favorable conditions, good crops can be grown without irrigation. Except in favored locations, however, the climate is too cold for anything but hardy cereal and root crops. What with the short seasons and droughts, crop failures are common. As a rule only parks[8] are suited for farming. Most forest lands are too rocky or too rough for successful cultivation, and even

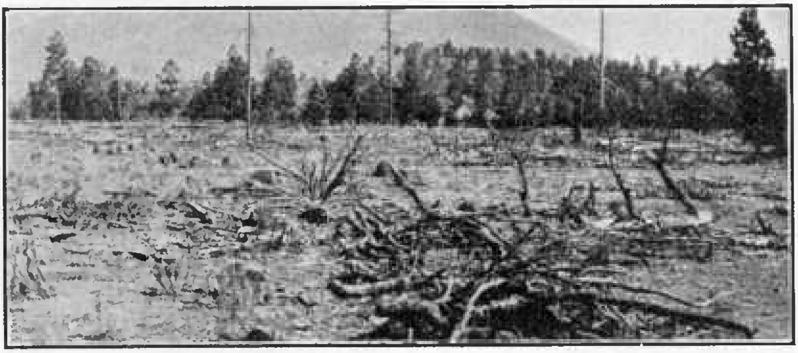

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FIGURE 6.—Clear cutting and fire in western yellow pine forests result in devastation. Centuries will be required to build up such areas to their full forest productivity

where soil and topography are favorable the expense of removing stumps is seldom warranted. (Fig. 6.)

Grazing is an important local industry in this type. Unfortunately it has been conducted in a manner highly detrimental to timber, water, and land resources. On thousands of acres stands of young pine seedlings have been destroyed or decimated. Where continued overgrazing has killed out much of the herbaceous cover, this, together with trampling, has resulted in erosion on a large scale.

DOUGLAS FIR ZONE

Although Douglas fir is generally regarded as the characteristic tree of this type (fig. 7), yet, unlike western yellow pine, it rarely occurs in pure stands in this region. Common associates are white fir, which often predominates on north slopes, limber pine or Mexican white pine (*Pinus strobiformis*), and blue spruce (*Picea pungens*). In the lower portion of the type western yellow pine and in the upper portion Engelmann spruce occur in mixture. Aspen is common throughout and extends well into the Engelmann

[8] The word "park" is applied locally to treeless areas within a forest.

spruce type above. (Fig. 8.) In old, well-stocked stands of conifers aspen almost disappears, but it usually asserts itself as soon as an opening is made. Burns on which the conifers have been completely destroyed often grow up to pure aspen, which in the usual course of succession is later replaced by conifers. Grasses usually are not abundant in the Douglas fir zone, except where the conifers

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FIGURE 7.—Pure stand of Douglas fir, Mount Graham, Ariz.

have been killed and aspen has not taken possession. The "prairies" of the Apache National Forest furnish another exception, if it may be assumed that this land was ever occupied by trees.

Under cover of the forest, herbaceous vegetation consists mostly of such plants as the sedges (*Carex* spp.), brake (*Peteridium aquilinum pubescens*), vetch (*Vicia americana*), columbine (*Aquilegia* spp.), *Frasera seabra*, and *Helenium hoopesii*. The bunch grasses found in open situations are the same as those in the western yellow pine zone. Either underbrush or aspen is more or less abundant wherever the stand has been thinned by fire or other agencies. A number of the brush species, including several alders, willows, maples, and locusts, attain tree form under favorable conditions. Of the distinctly shrubby plants, there are a blue and a red elderberry and several species of currant and gooseberry.

The volume, density, and composition of the timber stands vary greatly according to site and locality. In northern New Mexico 8,000 to 10,000 board feet is an average acre yield; in southern New Mexico and southern Arizona, average yields run about 20,000 board feet, and 40,000 feet is not uncommon. Most stands have been thinned by fire. This favors the invasion of western yellow pine in the lower altitudes and limber pine, aspen, and brush higher up. Usually the forest is uneven aged with dense reproduction, often

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FIGURE 8.—A mixed stand of Douglas fir, western yellow pine, blue spruce, and aspen

made up largely of white fir, under the old stand. Both Douglas fir and white fir attain large size, reaching maximum diameters of 3 to 4 feet, and heights of 140 feet. Mature stands are usually more than 200 years old, and trees 300 to 400 years old are not uncommon.

The average altitudinal limits of the Douglas fir zone range from about 8,000 to 9,500 feet. Since the zone is characterized mainly by steep slopes, aspect is fully as important as altitude and therefore any figures on altitudinal limits over extensive areas can be only rough approximations. Only a small proportion of the land is topographically adapted to agriculture. Rainfall is adequate for most farm crops, but the growing season is too short. Although grazing use is similar to that in the western yellow pine zone, serious damage is less widespread, owing in large measure to the shortness of the grazing season. Extensive lumbering operations are in progress in New Mexico, but very little cutting has been done in this zone in Arizona. Extensive areas in both States were devastated by fire prior to the establishment of organized protection. The greater portion of these burns has grown up to aspen and will eventually restock to conifers.

ENGELMANN SPRUCE ZONE

Engelmann spruce occupies the highest altitudinal zone of forest growth in the Southwest. (Fig. 9.) Typical Engelmann spruce stands occur almost exclusively on northerly exposures, even at the upper limits of the range. On steep, south-facing slopes and exposed ridges, bristlecone pine or limber pine usually predominates. These sites are so different from those of Engelmann spruce and the firs that where rather close distinctions are desired they are regarded as determining a separate forest type, notwithstanding the fact that a limber pine-bristlecone pine type is not generally recog-

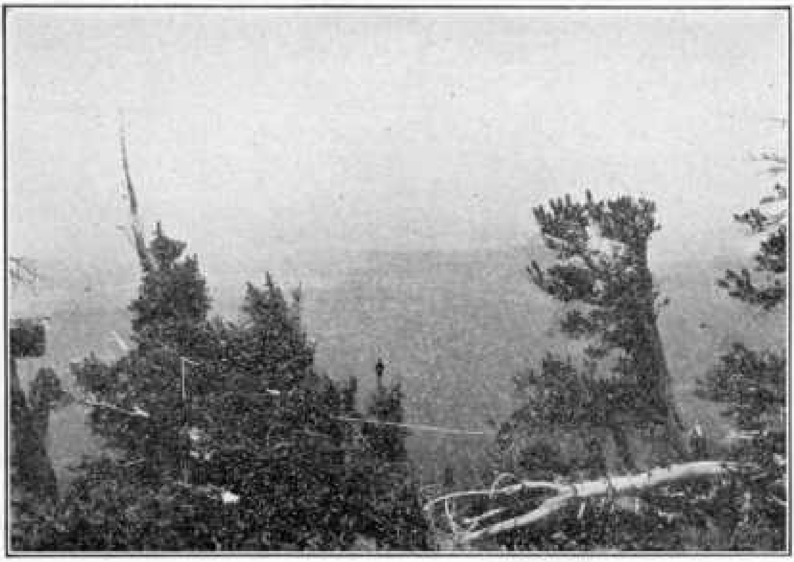

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FIGURE 9.—At 11,500 feet, Engelmann spruce still retains tree form but is dwarfed, and the tops above snow level are killed in winter by the terrific blasts of wind, snow, and sleet which cut off the leaves and even the bark on the windward side

nized by the Forest Service. Alpine fir or corkbark fir is a constant companion of the spruce. They are, however, shorter lived and tend to die out in mature stands.

In a dense spruce forest the floor is almost bare of either herbaceous or shrubby vegetation. Since snow is still on the ground well into the month of June, the soil remains moist even on the surface, except for short periods in early summer and in the fall. Mosses and lichens are much in evidence, though they seldom form a mat on the soil. Leaf litter is from 1 to 3 inches deep and usually forms a true leaf mold at the bottom. In the openings a touch of color is added by such plants as columbine, gentian, honeysuckle, and red elderberry. The shrubs and broad-leafed trees are much the same as in the Douglas fir type, but they do not extend to the upper portion of the Engelmann spruce type. In open situations one finds most of the grasses common to the western yellow pine type, but they are usually dwarfed. In addition, there are several alpine grasses and grasslike species such as *Phleum alpinum*, *Festuca saximontana*, *Trisetum montanum* and *T. spicatum*, *Carex heliophila* and *C. geophila*, and several species of Juncus.

Advance reproduction is present in various stages ranging from seedlings to poles, except under dense, even-aged stands. The well-known ability of spruce and fir to persist when shaded and undernourished enables both of these species to survive for many years under older trees in thickets so dense that growth is almost entirely checked. It is common to find trees of saw-timber size side by side with slender poles, all of nearly the same age. The pines are less able to persist under cover and are therefore absent from the dense stands, particularly on north exposures.

Aspen has much the same status here as in the Douglas fir zone. It takes possession of burns and other openings except toward the upper limits of the type, where it apparently encounters unfavorable conditions. However, spruce and fir, if seed trees survive, reproduce readily under any but an extremely dense aspen cover and eventually regain possession of the soil. Extensive areas in the high mountains of Arizona and New Mexico were swept by fires 40 to 50 years ago. Large portions of these areas have grown up to aspen and as a rule are being restocked by conifers. Most exceptions to this rule may be explained by lack of seed trees, but in a few places other factors appear to dominate. On considerable areas, particularly in the higher altitudes, aspen has not followed the fire. Here grasses and sedges have entered, and conifer reproduction is making slow progress.

Under favorable circumstances the spruce forest is capable of producing heavy stands of timber. The maximum possible yields are rarely realized under natural conditions, however, because of destructive competition in overstocked stands. A 250-year-old stand in the San Francisco Mountains was found to contain a volume of 44,000 board feet to the acre. It was ascertained, however, that originally a considerable proportion of this stand was corkbark fir. This had died out, leaving a pure stand of spruce. (Fig. 10.) Growth during the last half century has been almost at a standstill. The volume, including fir which had died, was probably at least as great at 200 years of age, or even younger, as at 250. A near-by stand of spruce and fir in about equal proportions which proved to be 180 years old, had a volume approximately the same as that on the first area. Although, over large areas the volume in the old forest is much lower, these figures are a good indication of what might be possible in young fully stocked stands under management. In overstocked stands both spruce and fir are small, few trees surpassing 18 inches d. b. h. and 80 feet in height. Free-standing trees reach a diameter of 30 inches and a height of 100 feet.

The Engelmann spruce type has been less exploited than any other type in this region. The stands are mostly inaccessible for logging under present economic conditions. Open situations, such as burns and natural meadows, furnish good summer grazing. There is practically no farming in this type, because of the short growing season and the general unsuitability of living conditions in these high altitudes. Although the timber resources are important, perhaps the greatest economic value of the Engelmann spruce type is its

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FIGURE 10.—Pure stand of mature Engelmann spruce 250 years old. Corkbark fir was formerly present, as is indicated by dead and down material

watershed value. Along with the Douglas fir type, it occupies the zone of heavy precipitation from which are fed the streams and underground water sources that mean so much to the Southwest.

CLIMATE

SOURCES OF DATA

The climatological data here presented are mainly from records of the United States Weather Bureau but are supplemented by data obtained from a special investigation carried on by the Southwestern Forest and Range Experiment Station in and near the San Francisco Mountains of northern Arizona. The independent study included measurements of soil temperature and soil moisture. During the summer of 1919, J. O. Veatch of the then Bureau of Soils made a general soil survey in northern Arizona, including detailed examinations of certain areas, in order to establish the relationship between soil and tree growth. Much of the information on soils has been obtained from Veatch's unpublished reports.

WEATHER BUREAU RECORDS

For obvious reasons the sparsely settled high-mountain regions are not so well represented by weather stations as the lower and more densely populated regions. In New Mexico there are, fortunately, several good sets of records for the western yellow pine, Douglas fir, and lower Engelmann spruce types. Arizona, however, has only three stations with continuous records in the western yellow pine zone, two with broken records in the Douglas fir zone, and none in the Engelmann spruce zone. Through the courtesy of Charles E. Linney of the New Mexico section, and Robert Q. Grant of the Arizona section of the Weather Bureau, it was also possible to make use of some records prior to their publication.

Because of the great yearly and periodic variation in precipitation, it was thought necessary to reduce the data from various stations to the same period as far as possible, in order that they might be comparable. This necessitated eliminating some of the oldest records. As a considerable number of the forest weather stations were established about 1909, the precipitation figures here used begin with that year. Regional and type summaries extend only through 1921, although records for individual stations have in many instances been carried through 1926.

Annual means of temperature do not fluctuate widely in successive years, and an average established by 10 years of record will not be departed from more than a degree or two in succeeding periods of similar length. For this reason it is not considered necessary that the periods of temperature observation at different stations be strictly contemporaneous. Most of the temperature summaries given in this bulletin extend to the end of 1921, but they begin at various dates, some more than 40 years ago. Except in the San Francisco Mountain series (which will be discussed later), and in a few other instances, the shortest temperature and precipitation records here used cover a period of six years. Because of the fact that nearly all values given in the tables and graphs represent the average of several stations, abnormalities due to short or noncontinuous records or to unrepresentative locations are in a measure neutralized.

ORIGINAL INVESTIGATIONS

In order to obtain data in the Douglas fir and Engelmann spruce forests in Arizona a series of temporary stations was maintained by the Southwestern Forest Experiment Station from 1917 to 1919, inclusive. This series extended from an elevation of 7,300 feet up the slopes of the San Francisco Mountains to timber line at 11,500 feet, representing the western yellow pine, Douglas fir (fig. 11), limber pine, and Engelmann spruce types and the upper limit of timber growth (fig. 12). A station was also maintained in the piñon-juniper zone, through the cooperation of Forest Ranger W. J. Cox, at Ash Fork, 55 miles west of the San Francisco Mountains. A temporary piñon-juniper station was maintained 15 miles southeast of the San Francisco Mountains during a portion of 1918. In all, there were 12 instrument stations, including 7 designated as substations and maintained during shorter periods in order to compare conditions within forest types. By tying in with Weather Bureau stations in the lower altitudes down to 1,000 feet at Phoenix, it was possible to obtain, within a direct distance of but little more than 100 miles, a series of records representing a vertical range of 10,500 feet and a range of climatic conditions embracing more or less regular gradations from arid-subtropical to humid-alpine.

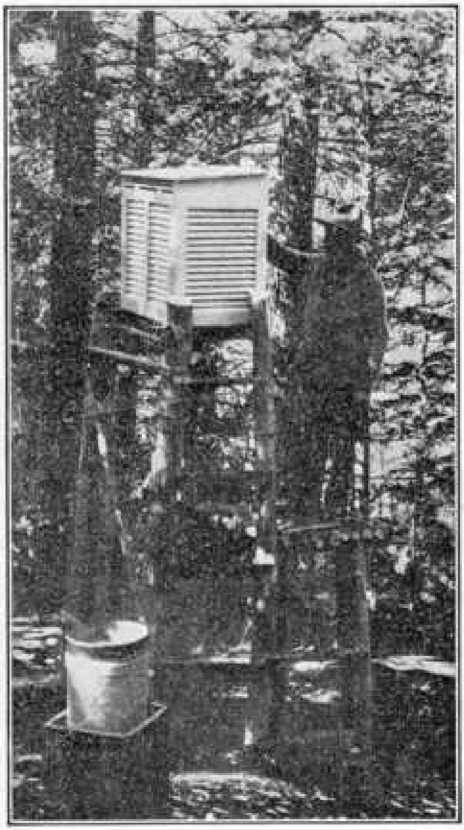
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FIGURE 11.—Douglas fir station 8A

Temperature and precipitation have been correlated with vegetation for this entire chain of stations, and in addition soil temperature and soil moisture were measured in and near the San Francisco Mountains. In presenting this and certain other material, such as temperature summations, the San Francisco Mountains have been treated as a separate unit because comparable data are not available in other sections.

The fact that the San Francisco Mountain records cover only three years may give rise to doubt as to their value, and it should be understood at the outset that no claim is made for these records as a measure of normal climatic conditions. At least 10 years are required to establish an acceptable norm, according to meteorologists, but they generally accept the principle, which is supported by the results of this investigation, that for the purpose of ascertaining relations between stations in the same locality a much shorter period will suffice. The San Francisco Mountain records are particularly important in this study because they represent true forest conditions. The stations extend nearly 2,000 feet higher than any others in Arizona and New Mexico; since the records were obtained contemporaneously and according to uniform methods,[9] they are directly comparable in the various types concerned; the use of thermographs

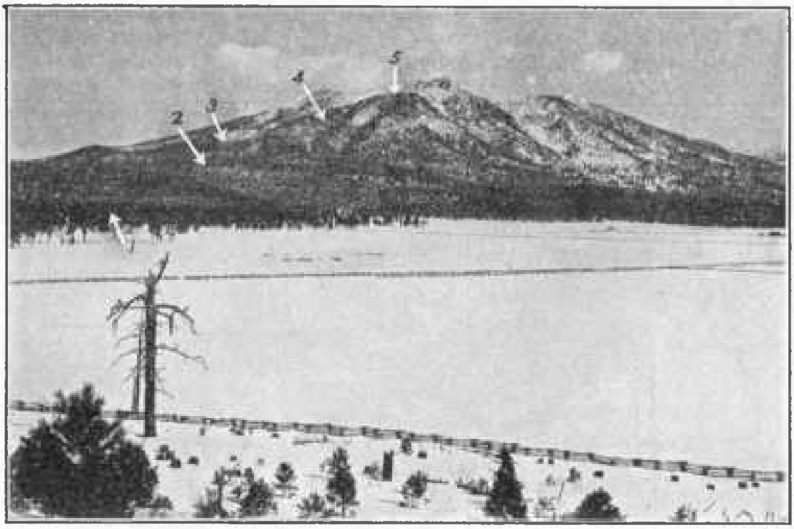

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FIGURE 12.—Fort Valley park and the San Francisco Mountains. The location of the western yellow pine, Douglas fir, limber pine, Engelmann spruce, and timber-line meteorological stations is indicated by 1, 2, 3, 4, and 5, repectively

at all stations has made it possible to compile temperature summations which integrate in various ways effective heat values; and the climatic data have been correlated with soil temperature, soil moisture, and vegetation. Their correlation with Weather Bureau

[9] With the exception of those selected to represent open situations, the stations were located in small openings within bodies of virgin forest. It is recognized that from a purely meteorological point of view, it would be preferable to avoid the local influence of forest cover. In this investigation, however, the endeavor is to study conditions as they exist within the forest, particularly with reference to young growth. At all the main stations due consideration was given to air drainage and free exposure to precipitation. The investigations required a weekly visit to each station in order to change thermograph sheets, keep instruments in proper adjustment, and record precipitation, evaporation, soil temperature, and various other data. During the winter months these trips were exceedingly strenuous. Except in 1917–18 the timber-line station could not be reached regularly between October and May. At times, snowstorms delayed the weekly visits to the Douglas fir and Engelmann spruce stations. A number of short breaks in the record are chargeable to this cause and to the occasional failure of instruments to function properly. War conditions brought about frequent changes in the personnel. Obviously the work suffered from these changes, despite close supervision by the writer. The following men served as observers at various times: Emanuel Fritz, Lenthal Wyman, T. S. Hansen, C. E. Behre, S. S. Van Boskirk, L. J. Arnold, J. E. Kintner, and F. W. Haasis. The most exacting and time-consuming part of the work was the compilation of data. This was efficiently handled by Maude E. Wilson during 1918 and 1919, and later by F. W. Hedlund and Eva C. Fleming, who also made extensive compilations of Weather Bureau records.

records covering longer periods will be discussed in the proper connection.

A detailed discussion of the methods of study applied in compiling the records in and near the San Francisco Mountains is given in the Appendix, page 134.

GROUPING OF DATA BY GEOGRAPHICAL DIVISIONS

Because of local differences, mainly in precipitation, the available climatic records were separated into four groups representing the following geographical divisions or regions: (1) Arizona, including all of Arizona except a narrow strip along the eastern border; (2) eastern Arizona and western New Mexico, covering a transition zone extending about 50 miles west and 100 miles east of the Arizona-

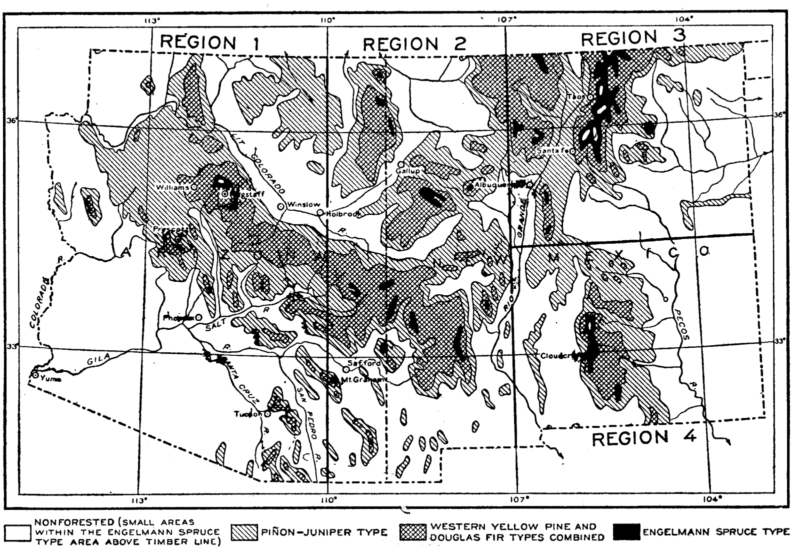

FIGURE 13.—Forest types and precipitation regions of Arizona and New Mexico. (Adapted from Natural Vegetation, a map by H. L. Shantz, Bureau of Plant Industry, and Raphael Zon, Forest Service, U. S. Department of Agriculture)

New Mexico State line; (3) north-central New Mexico; and (4) south-central New Mexico. (Fig. 13.) In addition to the importance of detecting local climatic differences, there is distinct value in the mutual control exercised by several sets of data on the same subject. This is the main reason for dividing New Mexico into a northern and southern region. Arizona might be divided in the same manner but for the fact that there are no adequate records for high altitudes in the southern part of the State. As it is, the data for the southern part are complementary to those of the northern part in that they fill out the lower extreme of the altitudinal series. Northern Arizona, or more specifically the San Francisco Mountain region, is treated as a separate unit with respect to certain data, such as soil temperature, soil moisture, and temperature summations which are not available or have not been compiled for other sections.

THE GROWING SEASON

The beginning and the end of the growing season are generally determined by the presence of sufficient heat for the growth of plants. This season is usually considered to be coincident with the frostless period (Table 1), but it is well known that many plants begin growth before the last frost in spring and are not injured by freezes which are destructive to more tender vegetation.

TABLE 1.—*Duration of frostless period in five forest types in northern Arizona, 1917 to 1919*

Forest type, station, and altitude	1917	Days	1918	Days	1919	Days
Piñon-juniper:						
Cosnino, 6,500 feet			June 1–Sept. 23	115		
Ash Fork, 5,100 feet	June 2–Oct. 18	139	May 31–Oct. 17	140	Apr. 17–Oct. 18	185
Western yellow pine:						
Fort Valley, 7,300 feet	June 13–Sept. 24	104	June 1–Sept. 16	108	June 15–Oct. 2	110
Flagstaff, 6,900 feet	June 7–Sept. 26	112	June 1–Sept. 23	115	June 4–Oct. 3	122
Walnut Canyon, 6,700 feet.	do	112	do	115	do	122
Douglas fir, 8,900 feet	June 3–Oct. 17	137	June 1–Oct. 17	139	June 3–Oct. 2	122
Engelmann spruce, 10,500 feet.	June 6–Sept. 23	110	June 1–Sept. 24	116	June 3–Sept. 28	118
Timber line, 11,500 feet	June 6–Sept. 22	109	June 2–Sept. 22	113	June 14–Sept. 22	101

Several plants in the western yellow pine zone of northern Arizona, among which may be mentioned *Poa fendleriana* and *Thlaspi fendleri*, make their major vegetative growth, blossom, and mature their fruit during the late spring, when frosts occur almost every night. The junipers, the piñon, and western yellow pine make their height growth during May and June, when severe freezes are by no means uncommon. The only native conifer in this region which has been observed to suffer frequently from spring frosts is Douglas fir, and this species is rarely injured in its native habitat. In both the Douglas fir and the Engelmann spruce types, the growing season corresponds closely to the frostless season because here spring growth is retarded by snow. In the western yellow pine and the piñon-juniper types, however, the growing season must be regarded as beginning considerably earlier than the period of no frost.

Cessation of growth in the autumn appears to be as independent of frost as is the inception of growth in the spring. Many plants continue to grow until the leaves are killed by frost; others are not injured by the first frost and continue more or less activity, particularly in the development of fruit, until checked by a severe freeze. But nearly all trees and shrubs in this region cease vegetative activity long before the first autumnal frost. All the conifers complete the development of new shoots and foliage by the middle of August. When diameter growth ceases is not definitely known for all species; in western yellow pine it is practically over by September 1. The high-mountain species mature their cones in September, usually before the first frost; in western yellow pine, however, the cones usually ripen in October after one or more severe freezes have occurred. Broad-leafed trees and shrubs may shed their leaves without being subjected to freezing temperature, although frost will hasten the process.

In the light of several recent investigations it appears that the growing season may be influenced by a number of factors other than frost. According to the findings of Garner and Allard (*18*), certain lengths of day favor vegetative growth whereas others favor fruiting. Since these relationships differ for different plants, no generalization can be made; but the possibility that this factor may influence the time when growth ceases is strongly suggested.

It may be assumed that certain temperatures are required for growth, but to determine the minimum growing temperature where many species are involved is no simple matter. Moreover, growing temperatures, even when accompanied by suitable moisture conditions, do not always insure growth. Coville (*15*) has carried on experiments which show that many trees and shrubs indigenous to temperate or cold climates do not continue to grow in the autumn when placed in a greenhouse but shed their leaves and become dormant, as when they are left out of doors. In Arizona, the customary June drought has an important bearing upon seasonal growth. Some plants mature their fruit and become dormant before this drought reaches its height; others show practically no signs of life until the summer rains begin in July. Blue grama belongs to the latter class. It makes only a slight start in May, apparently because of low temperature. In exceptional years when a considerable amount of rain falls in June or the latter part of May, luxuriant growth follows; but under normal conditions dormancy continues through June, the warmest month of the year, and into July, until moisture as well as temperature becomes favorable.

In view of these circumstances it seems futile to attempt to fix the limits of the growing season with any great degree of precision. It is probably 90 days longer in the woodland than in the Engelmann spruce zone, from the standpoint of temperature alone; differences in the intermediate types are gradational. The woodland, however, loses more than 30 days on account of drought, a loss experienced in less degree in the western yellow pine zone and rarely if at all in the Douglas fir and Engelmann spruce zones. In comparing seasonal averages or totals it is convenient to adopt a uniform period for all forest types or vegetational zones, even though this may not always coincide so well as might be desired with the growing season. It is not necessary or even desirable, however, that all factors be summarized for the same months of the growing season. For current air and soil temperature the 4-month period June to September, inclusive, seems better adapted than any other to the main forest types, though it is admittedly inadequate for the woodland and lower zones. In summaries attempting to show the total amount of heat as expressed in temperature summations, however, the difference between types is much more effectively brought out by adding the month of May to the above period, as will be shown in the discussion of this subject. The effect of precipitation, if considerable in quantity, continues several weeks after it falls and therefore growth during June, which is often rainless, may be greatly stimulated by May rains. For this reason, precipitation has been totaled for the period May to September, inclusive.

TEMPERATURES

Through general usage, the term "temperature," when not otherwise qualified, has come to mean temperature of the atmosphere. In such a study as this, however, it is necessary to distinguish between air temperature and soil temperature and also between air temperature and the temperature of the plant. The temperature of the air is measured by placing a thermometer in freely circulating air shielded from the direct rays of the sun. An ordinary thermometer exposed to the sun measures, imperfectly to be sure, the radiant heat energy of the sun rather than the temperature of the air. It is this radiant energy which heats the air, soil, and plants.

AIR TEMPERATURE

Air temperature is the best available index of heat as related to climate. It is also the most readily measured of all climatic factors. Another circumstance which contributes to the value of air temperature as a climatic index is the constancy of averages over long periods of time. Current fluctuations may be great, but when the averages are for periods of a year or longer the variations are seldom more than 10 per cent, whereas precipitation averages, for instance, often fluctuate as much as 100 per cent.

In Tables 2, 3, and 4 the records of several stations in each of the four regions have been combined under the various forest types or vegetational zones. Thus, under each zone the four regions are placed side by side, and the average of the four regions represents the zone over the entire territory covered. The various zones within each region may also be compared in these tables. They are more directly compared in Figures 14, 15, 16, and 17

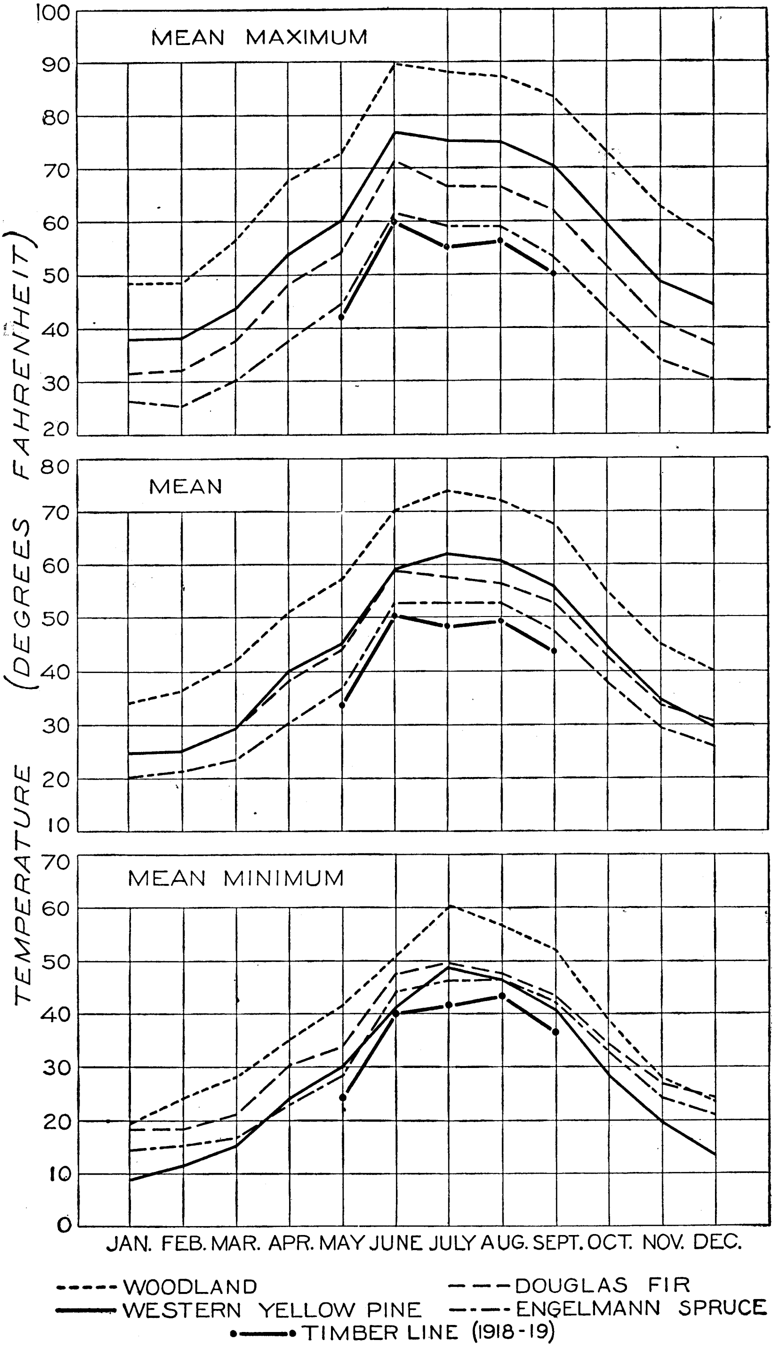

FIGURE 14.—Temperature by forest types in the San Francisco Mountains, 1917 to 1919, inclusive. (Original records)

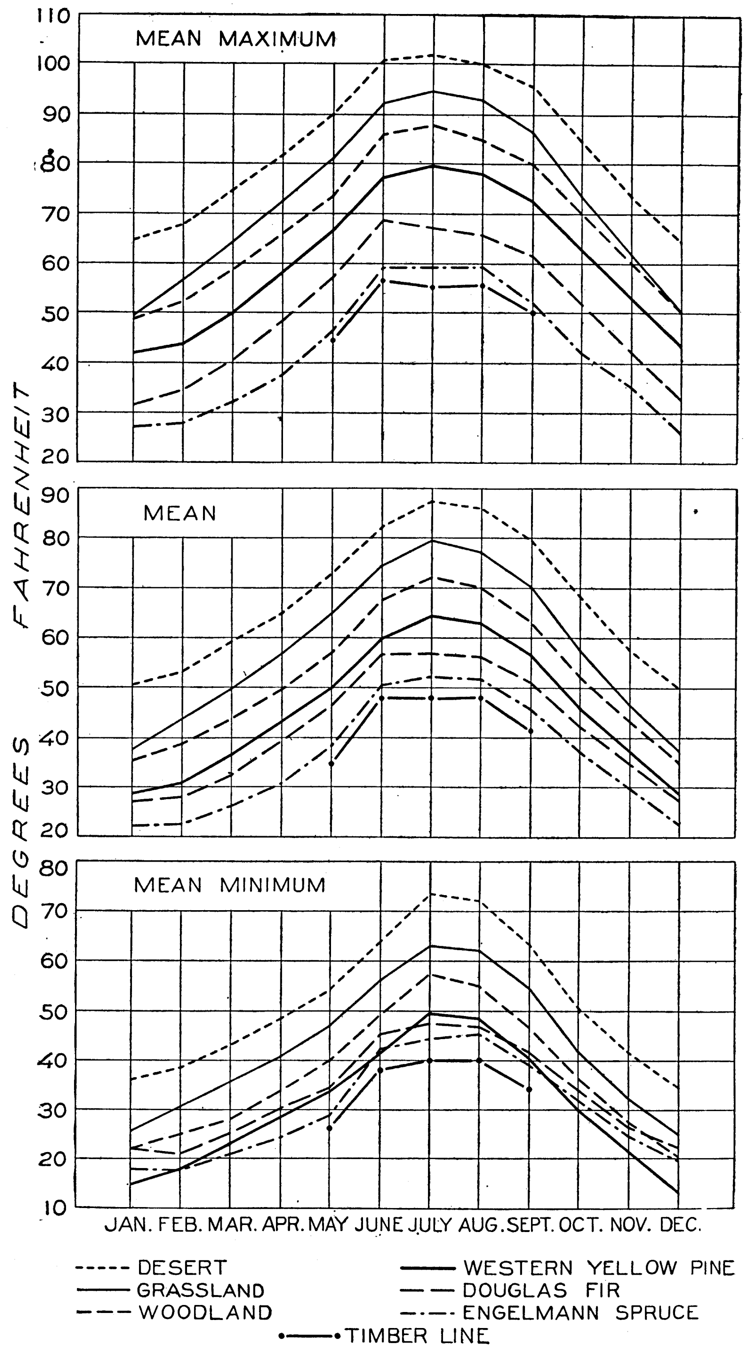

FIGURE 15.—Temperature by forest types, region 1, Arizona

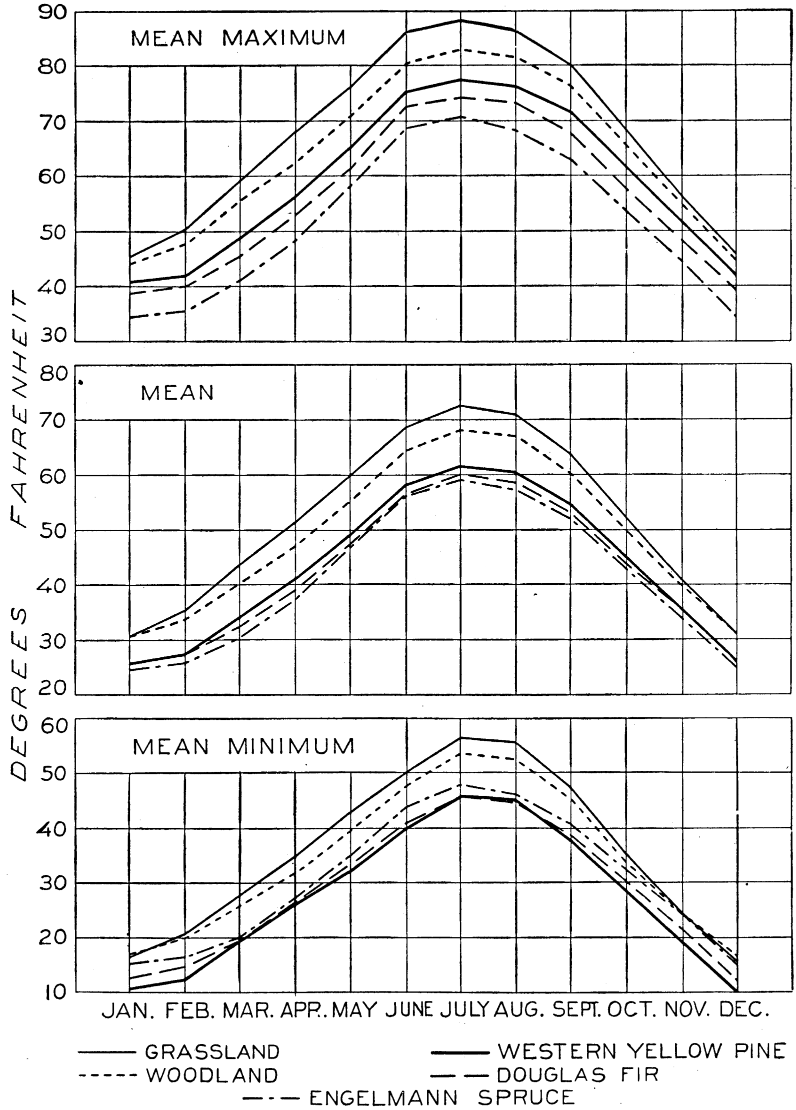

FIGURE 16.—Temperature by forest types, region 3, north-central New Mexico

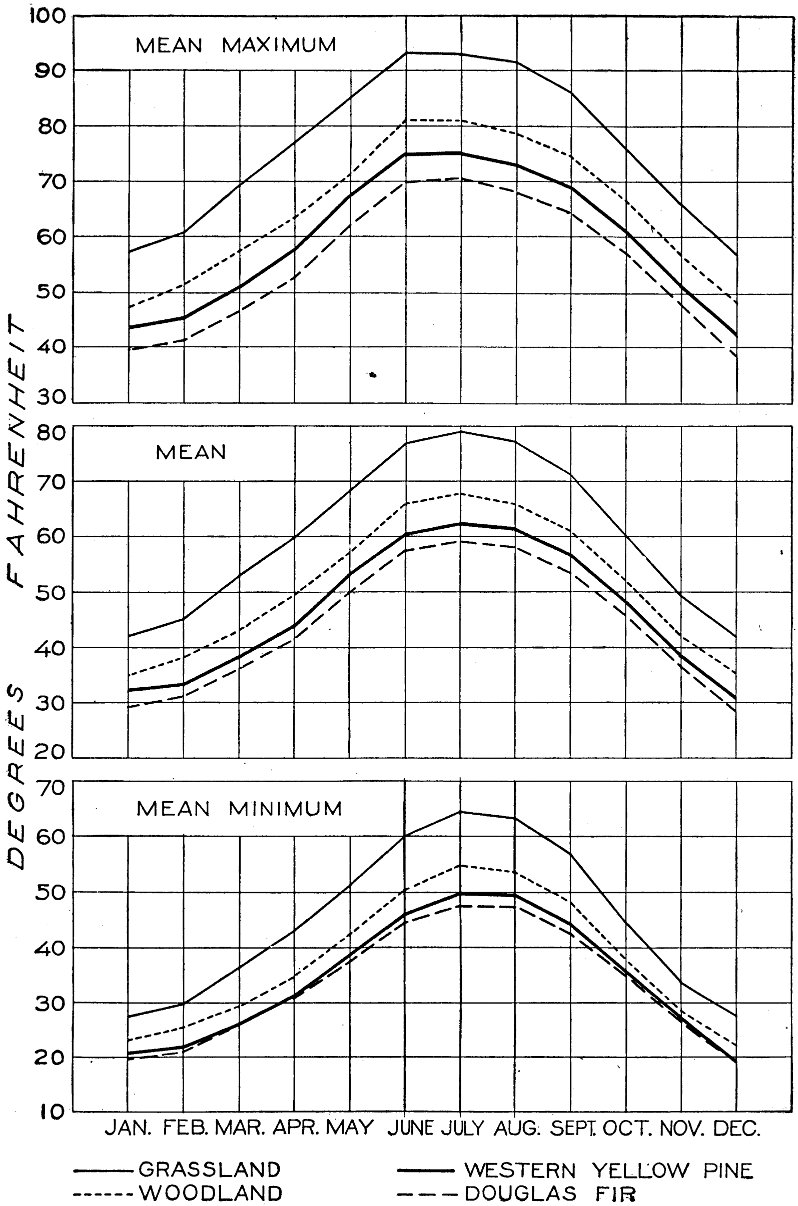

FIGURE 17.—Temperature by forest types, region 4, south-central New Mexico

TABLE 2.—*Mean maximum temperature by months in different vegetational zones and regions in Arizona and New Mexico, average of all years of record*

Region No.	Location	Stations [1]	Length range of records	Altitude	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Annual	June–Sept.
	DESERT																	
		No.	*Years*	*100 ft.*	° *F.*	° *F.*	° *F.*	° *F.*	° *F.*	° *F.*	° *F.*	° *F.*	° *F.*	° *F.*	° *F.*	° *F.*	° *F.*	° *F.*
1	Arizona	5	8–27	11–24	65.0	67.9	74.4	82.0	90.9	101.1	102.3	100.2	96.1	85.5	74.2	65.0	83.7	99.9
	GRASSLAND																	
1	Arizona	4	12–22	32–48	49.4	56.6	64.6	72.6	81.6	92.5	95.1	93.2	87.2	74.5	62.1	50.5	73.3	92.0
2	Eastern Arizona and western New Mexico	7	6–28	37–56	53.2	58.3	65.8	73.2	82.0	92.3	92.8	90.4	86.1	75.0	63.8	53.0	73.8	90.4
3	North-central New Mexico	5	20–24	49–70	45.4	50.3	59.8	68.2	76.6	86.6	88.5	86.9	80.6	69.1	56.4	45.3	67.8	85.6
4	South-central New Mexico	4	14–32	36–43	57.7	61.0	69.7	77.6	85.6	93.7	93.5	92.0	86.4	76.4	65.9	56.8	76.4	91.4
	Average				51.4	56.6	65.0	72.9	81.4	91.3	92.5	90.6	85.1	73.8	62.0	51.4	72.8	89.8
	WOODLAND (PIÑON-JUNIPER TYPE)																	
1	Arizona	7	6–22	47–69	48.9	52.5	58.8	66.6	73.5	86.2	88.0	85.6	81.1	71.0	60.5	50.4	68.6	85.2
2	Eastern Arizona and western New Mexico	14	3–40	51–70	50.4	53.6	60.1	67.7	76.2	86.2	85.7	83.3	79.2	70.2	60.1	49.7	68.5	83.6
3	North-central New Mexico	8	7–47	61–70	44.6	47.9	55.8	62.8	71.3	80.7	83.0	81.9	76.1	65.6	55.0	44.8	64.1	80.4
4	South-central New Mexico	3	6–22	62–71	47.4	51.2	57.3	63.6	71.5	81.2	81.2	79.0	75.2	66.9	56.9	48.2	65.0	79.2
	Average				47.8	51.3	58.0	65.2	73.1	83.6	81.5	82.4	77.9	63.4	53.1	48.3	66.6	82.1
	WESTERN YELLOW PINE ZONE																	
1	Arizona	3	13–27	67–73	42.1	43.9	49.4	58.0	66.2	77.7	79.8	78.2	73.1	63.4	53.8	43.5	60.8	77.2
2	Eastern Arizona and western New Mexico	5	3–14	65–85	44.4	49.4	54.8	62.0	71.5	82.7	81.7	79.5	75.3	65.4	55.7	45.2	64.0	79.8
3	North-central New Mexico	8	8–18	75–85	40.9	42.0	48.5	56.2	65.2	75.6	77.8	76.3	71.7	61.5	51.8	41.3	59.1	75.4
4	South-central New Mexico	2	11–18	66–86	43.9	45.3	50.8	57.3	67.5	75.2	75.3	73.7	69.7	61.4	50.9	42.3	59.4	73.5
	Average				42.8	45.2	50.9	58.4	67.6	77.8	78.6	76.9	72.4	62.9	53.0	43.1	60.8	76.5

	DOUGLAS FIR ZONE																	
1	Arizona [2]	1	3	89	31.1	32.2	37.6	47.9	54.3	71.6	66.9	66.6	61.9	52.3	40.8	36.7	50.0	66.8
2	Eastern Arizona and western New Mexico	1	5	85	45.9	47.3	52.5	55.6	67.1	76.6	75.5	73.9	71.5	62.1	55.2	43.9	60.6	74.4
3	North-central New Mexico	5	7–18	75–98	38.9	40.2	45.4	52.4	61.5	72.2	74.1	72.8	67.8	58.0	48.9	39.4	56.0	71.7
4	South-central New Mexico	1	18	86	39.8	41.0	46.6	52.7	62.1	70.2	70.9	68.5	64.8	57.0	47.5	38.5	55.0	68.6
	Average				38.9	40.2	45.5	52.2	61.2	72.6	71.8	70.4	66.5	57.4	48.1	39.6	55.4	70.4
	LIMBER PINE—BRISTLECONE PINE ZONE																	
1	Arizona [2]	1	1	100	34.9	28.1	35.7	45.8	53.4	63.4	61.5	63.4	55.7	41.1	37.5	33.7	46.2	61.0
	ENGELMANN SPRUCE ZONE																	
1	Arizona [2]	1	3	105	26.2	25.5	29.8	37.8	44.1	61.4	59.1	59.2	53.2	43.1	34.0	30.2	42.0	58.2
3	North-central New Mexico	2	7–10	94–98	34.5	35.7	40.7	48.3	58.4	68.9	70.4	68.3	63.1	53.8	44.8	34.9	51.8	67.7
	Average				30.4	30.6	35.2	43.0	51.2	65.2	64.8	63.8	58.2	48.4	39.4	32.6	46.9	63.0
	TIMBER LINE																	
1	Arizona [2]	1	2	115					43.5	60.1	55.4	56.4	50.9					55.7

[1] In each zone and region the records obtained from a number of stations at different altitudes and during periods of varying length have been averaged.

[2] Probable departure from 1909–1921 normal of Douglas fir, limber pine-bristlecone pine, Engelmann spruce, and timber-line records is as follows: January, −0.9; February, −2.6; March, −2.6; April, −0.2; May, −2.9; June, +2.2; July, −0.5; August, +0.4; September, +0.3; October, 0.0; November, −2.2; December, +3.8; annual, −0.4; June–September, −0.6.

TABLE 3.—*Mean minimum temperature by months in different vegetational zones and regions in Arizona and New Mexico*

Region No.	Location	Stations[1]	Length range of records	Altitude	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Annual	June–Sept.
		No.	*Years*	*100 ft.*	° *F.*	° *F.*	° *F.*	° *F.*	° *F.*	° *F.*	° *F.*	° *F.*	° *F.*	° *F.*	° *F.*	° *F.*	° *F.*	° *F.*
	DESERT																	
1	Arizona	5	8–27	11–24	36.5	38.9	43.2	48.1	54.4	63.9	73.2	72.6	65.0	52.6	42.9	35.9	52.3	68.7
	GRASSLAND																	
1	Arizona	4	12–22	32–48	25.3	30.1	35.3	40.6	47.2	56.2	63.7	62.6	55.3	42.6	32.8	25.5	43.1	59.4
2	Eastern Arizona and western New Mexico	7	6–28	37–56	21.7	25.7	30.7	35.5	42.3	51.3	59.6	58.8	51.0	38.3	27.9	21.8	38.7	55.2
3	North-central New Mexico	5	20–24	49–70	16.2	20.5	27.7	35.0	43.2	50.5	56.5	55.1	47.4	35.6	24.4	15.7	35.6	52.4
4	South-central New Mexico	4	14–32	36–43	27.3	30.2	37.0	43.3	51.6	60.6	64.8	63.5	57.0	44.6	33.8	27.4	45.1	61.5
	Average				22.6	26.6	32.7	38.6	46.1	54.6	61.2	60.0	52.7	40.3	29.7	22.6	40.6	57.1
	WOODLAND (PIÑON-JUNIPER TYPE)																	
1	Arizona	7	6–22	47–69	21.4	24.8	28.5	33.6	40.0	49.2	57.0	55.8	48.1	37.2	28.1	21.6	37.1	52.5
2	Eastern Arizona and western New Mexico	14	3–40	51–70	22.1	24.9	29.6	35.0	41.4	50.8	56.1	54.9	48.7	38.2	28.7	21.4	37.6	52.6
3	North-central New Mexico	8	7–47	61–70	17.1	19.9	25.9	31.8	39.4	47.8	53.7	52.3	45.2	34.1	24.3	16.5	34.0	49.8
4	South-central New Mexico	3	6–22	62–71	23.1	25.8	29.5	34.7	42.4	50.7	54.9	53.5	48.1	38.0	28.4	22.7	37.6	51.8
	Average				20.9	23.8	28.4	33.8	40.8	49.6	55.4	54.1	47.5	36.9	27.4	20.6	36.6	51.7
	WESTERN YELLOW PINE ZONE																	
1	Arizona	3	13–27	67–73	14.8	17.3	22.6	28.0	33.3	41.1	49.7	48.9	41.5	30.7	22.4	14.8	30.4	45.3
2	Eastern Arizona and western New Mexico	5	3–14	65–85	14.8	19.4	24.2	29.0	34.5	42.7	50.4	49.2	42.7	31.4	23.1	15.1	31.4	46.2
3	North-central New Mexico	8	8–18	75–85	10.5	12.6	19.6	26.1	32.7	40.0	45.9	45.0	37.8	28.3	19.0	9.9	27.3	42.2
4	South-central New Mexico	2	11–18	66–86	20.7	22.1	26.2	31.2	38.7	46.1	49.9	49.4	44.2	35.8	26.8	19.2	34.2	47.4
	Average				15.2	17.8	23.2	28.6	34.8	42.5	49.0	48.1	41.6	31.6	22.8	14.8	30.8	45.3

DOUGLAS FIR ZONE

1	Arizona [2]	1	3	89	17.8	18.5	21.0	29.5	33.7	47.3	49.1	47.0	43.4	34.6	26.7	23.9	32.7	46.7
2	Eastern Arizona and western New Mexico	1	5	85	12.1	14.1	20.0	23.5	28.9	36.7	44.7	43.6	35.2	26.8	19.3	7.8	26.1	40.0
3	North-central New Mexico	5	7–18	75–98	12.9	14.4	19.7	26.5	33.8	41.2	45.9	44.8	38.6	29.8	21.4	12.1	28.4	42.6
4	South-central New Mexico	1	18	86	19.9	21.2	26.1	30.8	37.4	44.4	47.5	47.5	42.7	34.9	26.3	19.1	33.2	45.5
	Average				15.7	17.0	21.7	27.6	33.4	42.4	46.8	45.7	40.0	31.5	23.4	15.7	30.1	43.7

ENGELMANN SPRUCE ZONE

1	Arizona [2]	1	3	105	13.8	15.3	16.8	23.6	28.3	44.0	46.2	46.5	41.5	32.8	24.0	21.2	29.5	44.6
3	North-central New Mexico	2	7–10	94–98	15.2	16.5	20.0	27.2	35.5	43.8	47.7	46.0	41.0	32.5	24.3	15.3	30.4	44.6
	Average				14.5	15.9	18.4	25.4	31.9	43.9	47.0	46.2	41.2	32.6	24.2	18.2	30.0	44.6

TIMBER LINE

1	Arizona [2]	1	2	115					25.8	40.6	41.6	41.5	36.7					40.1

[1] In each zone and region the records obtained from a number of stations at different altitudes and during periods of varying length have been averaged.

[2] Probable departure from 1909–1921 normal of Douglas fir, Engelmann spruce, and timber-line records is as follows: January, −4.4; February, −2.3; March, −4.0 April, −0.4; May, −0.4; June, +1.9; July, +1.3; August, −0.3; September, +1.1; October, +0.1; November, −1.4; December, +0.8; annual, −0.7; June–September, +1.0.

TABLE 4.—*Mean temperature by months in different vegetational zones and regions in Arizona and New Mexico*

Region No.	Location	Stations[1]	Length range of records	Altitude	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Annual	June-Sept.
	DESERT																	
		No.	*Years*	*100 ft.*	*° F.*	*° F.*	*° F.*	*° F.*	*° F.*	*° F.*	*° F.*	*° F.*	*° F.*	*° F.*	*° F.*	*° F.*	*° F.*	*° F.*
1	Arizona	5	8-27	11-24	50.8	53.4	58.8	65.0	72.6	82.5	87.8	86.4	80.6	69.0	58.6	50.4	68.0	84.3
	GRASSLAND																	
1	Arizona	4	12-22	32-48	37.4	43.4	50.0	56.6	64.4	74.4	79.4	77.9	71.2	58.6	47.4	38.0	58.2	75.7
2	Eastern Arizona and western New Mexico	7	6-28	37-56	37.4	42.0	48.2	54.4	62.2	71.8	76.2	74.6	68.6	56.6	45.8	37.4	56.3	72.8
3	North-central New Mexico	5	20-24	49-70	30.8	35.4	43.8	51.6	59.9	68.6	72.5	71.0	64.0	52.4	40.4	30.5	51.7	69.0
4	South-central New Mexico	4	14-32	36-43	42.5	45.6	53.4	60.4	68.6	77.2	79.2	77.8	71.7	60.5	49.8	42.1	60.7	76.5
	Average				37.0	41.6	48.8	55.8	63.8	73.0	76.8	75.3	68.9	57.0	45.8	37.0	56.7	73.5
	WOODLAND (PIÑON-JUNIPER TYPE)																	
1	Arizona	7	6-22	47-69	35.2	38.6	43.6	50.1	56.8	67.7	72.5	70.7	64.6	54.1	44.3	36.0	52.8	68.9
2	Eastern Arizona and western New Mexico	14	3-40	51-70	36.2	39.2	44.8	51.4	58.8	68.5	70.9	69.1	64.0	54.2	44.4	35.6	53.1	68.1
3	North-central New Mexico	8	7-47	61-70	30.8	33.9	40.8	47.3	55.4	64.2	68.4	67.1	60.6	49.8	39.6	30.6	49.0	65.1
4	South-central New Mexico	3	6-22	62-71	35.2	38.5	43.4	49.2	57.0	66.0	68.0	66.2	61.6	52.4	42.6	35.4	51.3	65.4
	Average				34.4	37.6	43.2	49.5	57.0	66.6	70.0	68.3	62.7	52.6	42.7	34.4	51.6	66.9
	WESTERN YELLOW PINE ZONE																	
1	Arizona	3	13-27	67-73	28.4	30.6	36.0	43.0	49.8	59.4	64.8	63.6	57.3	47.0	38.1	29.2	45.6	61.3
2	Eastern Arizona and western New Mexico	5	3-14	65-85	29.6	34.4	39.5	45.5	53.0	62.7	66.0	64.4	59.0	48.4	39.4	30.2	47.7	63.0
3	North-central New Mexico	8	8-18	75-85	25.7	27.3	31.0	41.2	49.0	57.8	61.8	60.6	54.8	44.9	35.4	25.6	43.2	58.8
4	South-central New Mexico	2	11-18	66-86	32.3	33.7	38.5	44.2	53.1	60.6	62.6	61.6	57.0	48.6	38.8	30.8	46.8	60.4
	Average				29.0	31.5	37.0	43.5	51.2	60.1	63.8	62.6	57.0	47.2	37.9	29.0	45.8	60.9

DOUGLAS FIR ZONE

1	Arizona [2]	1	3	89	24.4	25.4	29.3	38.7	44.0	59.4	58.0	56.8	52.6	43.4	33.8	30.3	41.3	56.7
2	Eastern Arizona and western New Mexico	1	5	85	29.0	30.7	36.2	39.6	48.0	56.6	60.1	58.8	53.4	44.4	37.2	25.8	43.3	57.2
3	North-central New Mexico	5	7-18	75-98	25.9	27.3	32.6	39.4	47.6	56.7	60.0	58.8	53.2	43.9	35.2	25.8	42.2	57.2
4	South-central New Mexico	1	18	86	29.8	31.1	36.4	41.8	49.8	57.3	59.2	58.0	53.8	46.0	36.9	28.8	44.1	57.1
	Average				27.3	28.6	33.6	39.9	47.4	57.5	59.3	58.1	53.2	44.4	35.8	27.7	42.7	57.0

ENGELMANN SPRUCE ZONE

1	Arizona [2]	1	3	105	20.0	20.4	23.3	30.7	36.2	52.7	52.6	52.8	47.4	38.0	29.0	25.7	35.7	51.4
3	North-central New Mexico	2	7-10	94-98	24.8	26.1	30.4	37.8	47.0	56.4	59.0	57.2	52.0	43.2	34.6	25.1	41.1	56.2
	Average				22.4	23.2	26.8	34.2	41.6	54.6	55.8	55.0	49.7	40.6	31.8	25.4	38.4	53.8

TIMBER LINE

1	Arizona [2]	1	2	115					34.6	50.4	48.5	49.0	43.8					47.9

[1] In each zone and region the records obtained from a number of stations at different altitudes and during periods of varying length have been averaged.

[2] Probable departure from 1909-1921 normal of Douglas fir, Engelmann spruce, and timber-line records is as follows: January, −2.6; February, −2.4; March, −3.3; April, −0.3; May, −1.6; June, +2.0; July, +0.4; August, 0.0; September, +0.7; October, 0.0; November, −1.8; December, +2.3; annual, −0.6; June-September, +0.8.

Temperature in Different Forest Types of the Same Region

In the comparison of temperatures in the several forest types of region 1 given in Tables 2, 3, and 4 and Figures 14 and 15 (to which records for the desert, grassland, and alpine-sedge land (timber line) have been added to show the extreme range), the outstanding feature is the irregular decrease in the mean minimum[10] temperature from the lowest to the highest altitudes in contrast with the regular decrease in the mean maximum. This irregularity in the mean minimum is most conspicuous in the relation between the western yellow pine, Douglas fir, and Engelmann spruce types. In the western yellow pine forests at Fort Valley and Flagstaff nights are often colder by several degrees in the winter and autumn months than in the Douglas fir and Engelmann spruce forests. (Table 5.) This phenomenon, known in meteorology as temperature "inversion," is not uncommon in mountain regions. It is merely a manifestation of the well-known fact that cold air tends to drain off the high places and settle in the low places. In this case all the stations are situated so as to avoid stagnation of the air as far as possible, but the mountain stations are on much steeper slopes than the western yellow pine and lower stations and therefore have better air drainage.

Table 5.—*Lowest temperatures, by months, at various stations in northern Arizona, 1918*

Forest type, station, and altitude	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
	° F.	° F.	° F.	° F.	° F.	° F.	° F.	° F.	° F.	° F.	° F.	° F.
Grassland:												
Kingman, 3,300 feet	21	21	28	27	35	49	53	50	51	38	24	11
Winslow, 4,800 feet	−9	12	18	17	30	40	52	44	38	23	14	−1
Piñon-juniper, Ash Fork, 5,100 feet	0	14	23	24	31	41	50	46	37	27	11	9
Western yellow pine:												
Williams, 6,700 feet	−3	2	12	18	21	28	39	35	26	18	0	−7
Flagstaff, 6,900 feet	−13	3	11	16	18	32	42	36	25	16	−4	−10
Fort Valley, 7,300 feet	−13	4	6	15	12	33	40	34	25	15	−4	−10
Douglas fir, 8,900 feet	−2	4	14	18	23	39	43	41	33	20	8	−2
Engelmann spruce, 10,500 feet	−6	2	9	13	19	35	39	38	32	17	2	−6
Timber line, 11,500 feet	−3	−2	9	5	13	30	34	33	29	10	2	------

Although the lowest night temperatures frequently occur at relatively low altitudes, the lowest day temperatures are found at the highest altitudes, as may be readily sensed by the mountain climber without the aid of instruments. As one ascends the slopes of a high mountain, the nights become little if any colder, but the days are decidedly colder. In the spruce forest the temperature in winter sometimes remains below freezing continuously for a week at a time, and in summer it rarely reaches 70° F. It is the low day tempera-

[10] The terms "mean maximum," "mean minimum," and "mean" temperature are used in conformity with Weather Bureau usage. The mean maximum temperature is the arithmetical average of the daily maxima. Usually the mean maximum is computed for each month, and the average of all the monthly mean maxima gives the mean maximum for the year. The mean minimum temperature is computed in the same way as the mean maximum. Mean temperature is designed to express the average temperature for the day, month, or year. The daily mean is usually calculated by taking the mean of the highest and lowest readings for the day. The monthly or annual mean is the arithmetical average of the daily means for the period involved, and also of the mean maximum and the mean minimum for the month or year.

tures, as reflected largely in the maxima, that constitute the vital heat deficit in the high altitudes.

The question has been raised whether the Douglas fir, Engelmann spruce, and timber-line records in the San Francisco Mountains, covering only three years, are comparable with the longer records in the western yellow pine and lower zones. Reference has already been made to the irregularities in the mean minimum. This condition, however, also appears in the New Mexico series (figs. 16 and 17) in which the Douglas fir and Engelmann spruce records cover 10 years or more and, in the case of figure 16, are the average of several stations. The point at issue is, to what extent do the 1917–1919 records in the Douglas fir and Engelmann spruce types and at timber line represent normal temperature conditions for this locality? An attempt has been made to answer the question by ascertaining how closely the 1917–1919 records in the western yellow pine type correspond to the records for a longer period.

Footnote 2 in Tables 2, 3, and 4 gives the monthly departures of the 1917–1919 means from the 1909–1921 norm at the control station in the western yellow pine type of the San Francisco Mountains. According to the annual means, the 1917–1919 period averaged 0.6° F. colder than normal. The greatest monthly departure from the norm was −4.4° in the minimum temperature for January. Further inspection shows that generally the departures are greatest in the minimum temperature and during the winter months. These figures are thought to be fairly accurate indices of seasonal and annual normality, but they are probably less reliable when applied to a single month. For this reason, the writer has hesitated to correct the monthly means in Tables 2, 3, and 4. In Figure 15, however, the monthly departures have been applied to the Douglas fir, Engelmann spruce, and timber-line records. The effect in general has been to harmonize the graphs. A notable exception is the minimum temperature for January. Figure 14 is plotted from the original data, the period of 1917–1919 being used in all types. It should be noted that these graphs are almost as regular as those based on longer periods in Figure 15.

From the foregoing analysis it is concluded that the Douglas fir, Engelmann spruce, and timber-line records obtained in the San Francisco Mountains in 1917–1919 and presented in Tables 2, 3, and 4 are directly comparable to records for the same period from other stations in the same region; but that if it is desired to compare these records with those for longer periods in the same or different regions, the departures indicated in the footnotes to Tables 2, 3, and 4 should be applied. As has previously been stated, however, too much reliance should not be placed on these departures as corrections for single months. This precaution is especially necessary with regard to minimum temperatures, for which there appears to be no such thing as a norm in mountain regions. This erratic behavior of the minimum presents a problem which apparently can not be wholly solved by long-time records. Inversions which cause the minimum-temperature graphs of the Douglas fir and Engelmann spruce types to cross and recross that of the western yellow pine type should be regarded as representing actual conditions rather than as being faulty records.

VARIATIONS IN THE WESTERN YELLOW PINE ZONE

During a period of five years (from 1909 to 1913, inclusive), air temperature, precipitation, wind, humidity, and evaporation were measured by the writer (*31*) in the Fort Valley park, a flat, treeless valley more than a mile in diameter, bordering the forest in which a permanent meteorological station is maintained. The records show daily maximum temperatures averaging 0.9° F. higher in the valley than in the forest. Daily minima averaged 6.4° lower and were often as much as 10° or 15° lower in the park than in the forest. The slightly higher day temperatures in the treeless area are attributed to better insolation, and the extremely low night temperatures in the park are due in part to absence of tree crowns to reduce radiation but mainly to drainage of cold air into the valley, which is from 25 to 50 feet lower than the surrounding forest.

In another locality, about 12 miles farther south, away from the immediate influence of the mountains, temperature was measured in 1910 at two stations about a quarter of a mile apart, similarly situated as to topography, but one in a virgin stand of western yellow pine and the other on an adjoining area where practically all the trees had been removed by logging. Here, as at Fort Valley, mean maximum temperature averaged about 1° F. higher in the open situation; but the minimum temperatures, instead of being many degrees lower in the open, were only from 2° to 3° lower. Evidently the reduction of radiation by the tree canopy was primarily responsible for the higher minimum temperatures in the forest.

The data available indicate that low temperatures become more moderate as the distance from high mountains increases. Thus Flagstaff, situated 8 miles farther from the San Francisco Mountains and only 400 feet lower than Fort Valley, has mean minimum temperatures averaging 2.7° F. higher than the latter station. At Williams, 30 miles farther from the San Francisco Mountains and only 150 feet below Flagstaff altitudinally, minimum temperatures average 1.9° higher than in Flagstaff. Both Flagstaff and Williams are so situated that they receive cold-air drainage from the surrounding country. But the nearest mountain to Williams, although not more than 5 or 6 miles distant, reaches an altitude of only 9,250 feet above sea level, or 3,500 feet less than that of the San Francisco Mountains.

VARIATIONS IN THE DOUGLAS FIR ZONE

In the Douglas fir zone of the San Francisco Mountains, contemporaneous records for different situations in the same locality are not available. In 1911 and 1912, however, records were kept during the summer months at a station about 2 miles distant from the one employed in the 1917–1919 series. As compared with the Fort Valley records, both stations show about the same general relation, namely, lower maxima but higher minima. The Douglas fir type through Arizona and New Mexico occurs almost invariably in rugged country, usually on slopes or benches and rarely, if ever, on broad, flat mesas characteristic of the western yellow pine type of the Colorado Plateau. The only situations in the Douglas fir zone which might be subject to abnormally low temperatures are the bottoms of canyons and a few basins.

VARIATIONS IN THE ENGLEMANN SPRUCE ZONE

The main Engelmann spruce station was on a steep northwest slope of the San Francisco Mountains in one of the heaviest pure stands of mature spruce in the Southwest. During 1919 and 1920, supplementary records were kept in an opening 150 feet in diameter on a ridge about 100 yards directly above the main spruce station. The ridge at this point is about 200 feet wide and breaks off to the south into steep, grassy slopes where spruce, corkbark, fir, and bristlecone pine grow in clumps. Table 6 gives the mean maximum and mean minimum temperatures by months at the northwest slope and the ridge stations. The outstanding differences between the two stations is the much higher day temperature and lower night temperature on the ridge. These differences are caused in part by absence of tree cover at the ridge station.

TABLE 6.—*Comparison of temperatures on a ridge and a steep northwest slope, by months, 1919*

MEAN MAXIMUM TEMPERATURE

Station No.	Forest type and exposure	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	June to Sept.
	Engelmann spruce:	° F.	° F.	° F.	° F.	° F.	° F.	° F.	° F.	° F.	° F.
10B	Ridge	43.2	51.6	65.9	60.2	62.8	55.3	39.4	33.9	29.2	61.0
10A	Northwest slope	40.0	48.5	62.1	58.5	60.3	52.2	36.2	32.8	29.9	58.3
	Timber line:										
11A	Ridge		48.1	60.7	55.9	59.0	49.6				56.3
11B	Northwest slope			62.0	55.5	58.5	50.4				56.6

MEAN MINIMUM TEMPERATURE

Station No.	Forest type and exposure	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	June to Sept.
	Engelmann spruce:										
10B	Ridge	24.3	32.3	41.7	45.6	45.2	39.7	25.7	22.2	17.2	43.0
10A	Northwest slope	25.2	33.1	43.1	47.1	47.4	41.2	26.1	23.6	20.1	44.7
	Timber line:										
11A	Ridge		29.0	37.7	41.9	43.3	36.3				39.8
11B	Northwest slope			36.1	43.6	43.0	36.1				39.7

VARIATIONS AT TIMBER LINE

The main timber-line station was on a ridge about 100 yards wide, facing the southwest. In the preliminary report on this investigation (*32*), the subnormal development of the trees at this station is attributed to wind rather than to low temperature. On the northwest slope, just over the ridge about 100 yards from the ridge station, the spruce timber stops abruptly, there being practically no transition zone of bushy or trailing spruce beyond the line of erect trees, as is the case on the ridge. A thermograph was operated just outside the timber line during the months of June, July, August, and September, 1919. The difference in both mean maximum and mean minimum at the two stations (Table 6) is very slight and fluctuates from month to month. Wind movement during October, 1918, was more than twice as great on the ridge as on the slope. (Table 17).

Although regions 2, 3, and 4 have not been studied in the same detail as region 1, available information indicates a similar relation between forest types. Region 3, which has satisfactory records up to the lower portion of the Engelmann spruce type, shows the same uniform decline in maximum temperature and the same irregular decline in the minima from the lower to the higher zones, with frequent inversions between the western yellow pine and the Engelmann spruce types. The minima in region 4 lack much of the irregularity found in regions 1 and 3, but the records extend only to the lower portion of the Douglas fir type.

Temperature of the Same Forest Type in Different Regions

In comparing physical conditions of a given forest type in different regions allowance must be made for a number of circumstances which operate against absolute harmony. In the first place, more or less variation is known to exist within a given type even in the same locality; therefore, a station near the upper limit of a type in Arizona would be expected to show conditions somewhat different from those at a station near the lower limits of the same type in New Mexico. The main discrepancy, however, arises from the fact that some of the records which it has been necessary to use are not truly representative. Even when a type in a given locality is represented by several stations the compensating influence of averages may not always overcome the difficulty. In north-central New Mexico, for instance, all three stations listed under Engelmann spruce are too near the lower edge of this type to give a true expression of conditions prevailing generally in the Engelmann spruce forest.

Tables 2, 3, and 4 show a reasonably close agreement between the four regions, considering the deficiency of data in some instances. In the grassland, woodland, and western yellow pine zones the stations are most numerous, and here the agreement is closest. The wide discrepancies in the records for Douglas fir and Engelmann spruce are attributable partly to incomplete or unrepresentative data. The Douglas fir type is well represented in northern New Mexico; in each of the other three localities it has but one station. In contrast to the Engelmann spruce stations in northern New Mexico, all of which are too near the lower border of the type, the one station in Arizona is well located, and its records, although they cover only three years, are probably more representative of temperature conditions in the Engelmann spruce type.

The general course of the graphs in Figures 14, 15, 16, and 17, for the several regions is very similar except for the month of June, when those for Arizona shoot upward in a manner which suggests abnormality. Doubtless the sharp rise in the Douglas fir and Engelmann spruce graphs for Arizona is exaggerated in degree, but that it represents a real condition is indicated by the fact that it is also present in the western yellow pine and piñon-juniper graphs, both based on a period of 13 years. This rapid rise in temperature during the month of June is apparently directly associated with the dry, clear weather which usually prevails in Arizona during this month, but which is less pronounced in New Mexico. The disappearance of snow on the mountains may also be a factor, especially in minimum temperatures.

Excepting the grassland, which covers a very wide range of conditions, and the Engelmann spruce type, in which data are very limited, the extreme differences within a type are rarely more than 6° F. As a rule there is closer agreement during the growing season than in winter.

Temperature Summations

As a measure of heat in relation to plant growth, the mean temperature, whether it be the daily, monthly, or annual mean, is unsatisfactory because night temperatures, which may be neutral as far as growth is concerned, are weighed against effective day temperatures.[11] In the San Francisco Mountains of northern Arizona, the mean annual temperature from 1917 to 1919, inclusive, was 41.5° F. in the Douglas fir type and 42.2° in the western yellow pine type. This variation of 0.7° would indicate differences too small to be of any consequence; yet any one familiar with conditions surrounding the two stations from which these records were obtained can not fail to note a most profound difference in both temperature and vegetation. Further inquiry into the records shows strikingly lower day temperatures and higher night temperatures in the Douglas fir zone than in the western yellow pine zone. Thus it comes about that when the daily maxima and minima are averaged, nearly the same mean daily temperature is obtained in both types. This close relation exists only during the winter, spring, and fall months. In winter, the Douglas fir station sometimes shows a mean monthly temperature actually higher than that of the yellow pine station, but during July, August, and September there is a wide margin in favor of the western yellow pine zone.

Further inspection of the graphs in Figures 14, 15, 16, and 17 brings out very clearly the disturbing effect of inversions in minimum temperature upon the daily mean. The graphs for mean maximum temperature, however, are remarkably free from irregularities. The uniform relation between mean maximum temperatures of various stations observed in all records in the Southwest has led the writer to regard this factor as far more reliable than mean temperature as an index of temperature relations. This view is strengthened by the indications, which will be discussed later, that in this particular study maximum values are of far more importance than minimum values. The mean maximum provides a good measure of the highest intensities attained, but it does not take into account the duration of these intensities.

Several schemes designed to integrate intensity and duration of temperature have been devised. As usually employed, however, these methods do not give adequate expression to intensity, because they are based on the mean daily temperature.

[11] Clements and Weaver (*14*) have improved on the conventional method of computing mean temperature by separating day means from night means.

Merriam (*29, p 54, f. n. 2*) used a method which he described as follows:

> In computing the sum of the positive or effective temperatures a minimum temperature of 6° C. (43° F.) has been assumed as marking the inception of the period of physiological activity in plants and of reproductive activity in animals. The effective temperatures or degrees of normal mean daily heat in excess of this minimum have been added together for each station, beginning when the normal mean daily temperature rises higher than the 6° C. in spring and continuing until it falls to the same point at the end of the season. The sums thus obtained were platted on a large scale map of the United States and connected by isotherms, which were found to conform in the most gratifying manner with the northern boundaries of the several life zones.

The minimum temperature referred to in the above description as marking the lower limit of physiological activity is in reality the lowest daily mean. In other words, when the computed daily mean falls below 43° F. the temperature for that day is regarded as ineffective, notwithstanding that there may have been several hours when the current temperature was above 43°. Evidently it is not assumed that 43° marks the lower limit of growth, but rather that when the daily mean is below this point effective temperatures are not likely to occur. In some investigations 42° and in others 32° have been used instead of 43°. When one considers the variation in heat requirements in different plants, any minimum limit must be regarded as more or less arbitrary. In spite of its shortcomings, the most obvious of which are the uncertain significance of mean temperature and the variability in minimum heat limits, this method was used effectively by Merriam 30 years ago in what is still regarded as an authoritative work on temperature integration in its relation to the distribution of plants and animals.

Another method, known as the exponential indices,[12] is based upon the principle of Van't Hoff and Arrhenius that the velocity of chemical reaction approximately doubles with a rise in temperature of 18° F. The indices of temperature efficiency are calculated on the assumption that general plant activity occurs at unity rate when the daily mean temperature is 40° and that this rate is doubled with each rise of 18° in the daily mean. This principle seems to apply only within certain limits of temperature, even in purely chemical problems; the limitation is probably still greater when applied to plant growth. In addition, the method is open to criticism because it employs the mean daily temperature instead of the actual temperature during the hours of major physiological activity.

Probably the most effective method of integrating temperature is what is known as the physiological indices of temperature efficiency, based upon experiments by Lehenbauer (*24*). In these experiments, maize seedlings were grown at different temperatures, and the rate of growth during a period of 12 hours was carefully measured for all. The temperatures were in regular gradations of 1°, ranging from 12° to 43° C. Thus, one lot of plants was grown at 12°, another at 13°, another at 14°, and so on through the scale. Lehenbauer found that 32° was the optimum temperature for growth under the conditions surrounding his plants, but he also stated that the optimum is without meaning unless duration as well as intensity

[12] The review of this method and of the physiological indices method is taken largely from Livingston and Shreve (*26*).

is considered. Livingston, using Lehenbauer's data as a basis, has prepared a table, reproduced here as Table 7, giving growth values corresponding to each single degree of temperature from 36° to 118° F., considering the growth at 40° as unity. According to this table, the rate of growth increases with rise in temperature up to 89° and then falls off gradually, reaching the zero point at 118.4°. A logical development of this method for studies in forestry would be to determine the physiological indices of growth for forest trees instead of maize seedlings. Until this is done there can be no assurance that it provides a better expression of temperature with reference to tree growth than is afforded by some of the simpler methods.

TABLE 7.—*Physiological indices of temperature efficiency for growth, based on Lehenbauer's 12-hour exposures with maize seedlings* [1]

Temperature	Index	Temperature	Index	Temperature	Index	Temperature	Index	Temperature	Index	Temperature	Index
°F.		°F.		°F.		°F.		°F.		°F.	
36	0.111	50	6.333	64	30.000	78	90.667	92	113.444	106	21.889
37	.222	51	7.111	65	33.333	79	95.000	93	108.333	107	16.778
38	.342	52	8.167	66	37.222	80	98.667	94	103.333	108	12.556
39	.667	53	9.222	67	41.333	81	103.000	95	96.000	109	9.444
40	1.000	54	10.333	68	46.000	82	106.889	96	91.444	110	7.000
41	1.333	55	11.667	69	50.833	83	110.778	97	85.000	111	5.222
42	1.667	56	12.778	70	56.000	84	115.000	98	79.444	112	3.778
43	2.000	57	14.444	71	60.333	85	118.111	99	73.111	113	2.778
44	2.344	58	16.111	72	65.333	86	120.000	100	66.667	114	2.000
45	3.000	59	17.778	73	69.000	87	121.222	101	60.000	115	1.444
46	3.500	60	19.883	74	73.667	88	122.000	102	52.667	116	1.000
47	4.000	61	22.000	75	78.111	89	122.333	103	44.444	117	.500
48	4.778	62	24.333	76	82.333	90	121.667	104	36.000	118	.111
49	5.500	63	27.111	77	86.556	91	117.667	105	28.667		

[1] From (*26*).

Proper application of the table of physiological indices calls for a true measure of air temperatures, which is not afforded by the daily mean. It should be borne in mind that Lehenbauer's experiments were conducted with plants exposed to constant temperatures. The growth rate given for a temperature of 60° F. means a constant temperature of this intensity, not an average of readings ranging from 40° to 80°. The efficiency corresponding to a daily mean temperature of given magnitude may be far different from that obtained by summing the indices for the various components of this daily mean. Where thermograph records are available, errors from this source may be greatly reduced by dividing the day into short periods of uniform length, determining the efficiency of each separately, and taking the average of these values as the efficiency for the entire day. The 2-hour intervals marked on standard thermograph sheets are convenient and are probably sufficiently short for most purposes, although a change of as much as 30° is sometimes recorded in two hours. The values obtained in this way are entered in column 5 of Table 8, and those derived from the daily mean temperature are entered in column 4. It is evident that the two sets of values bear no constant relation to each other. The writer has no hestitation in saying that the values computed from 2-hour temperature means are the more reliable. In the western yellow pine type, the differences are much greater than in the Engelmann spruce type, owing probably to a greater daily range in the pine type. In fact, the differences in the spruce forest are rather small, and this suggests that in climates of even temperature the daily mean might give fairly good results.

TABLE 8.—*Comparison of physiological temperature efficiency computed from daily means and means for 2-hour periods, 1918*

WESTERN YELLOW PINE ZONE

Date	Daily temperature: Maximum	Daily temperature: Mean	Physiological efficiency: Based on mean daily temperature	Physiological efficiency: Based on temperature by 2-hour periods
	°F.	°F.		
June 1	68.8	52.8	9.22	17.22
2	75.5	54.2	10.33	28.01
3	75.7	56.5	12.78	31.23
4	77.0	56.3	12.78	37.97
5	76.2	57.0	14.44	38.73
6	79.0	58.4	16.11	39.04
7	77.7	60.2	19.88	41.22
8	77.5	59.6	19.88	37.47
9	83.0	63.2	27.11	51.50
10	86.3	67.2	41.33	56.97
Total or mean	77.7	58.5	183.86	379.36
June 11	88.9	68.8	50.83	66.12
12	88.2	68.0	46.00	45.87
13	81.9	66.4	37.22	44.29
14	81.2	65.4	33.33	40.56
15	76.6	62.0	24.33	31.22
16	76.9	62.5	24.33	31.99
17	81.0	66.2	37.22	37.77
18	79.0	63.4	27.11	34.54
June 19	78.0	63.4	27.11	31.71
20	79.0	63.4	27.11	43.10
Total or mean	81.1	64.95	334.59	407.17
June 21	77.8	66.2	37.22	28.80
22	70.0	61.2	22.00	21.00
23	73.5	62.8	27.11	28.65
24	77.6	61.4	22.00	33.47
25	81.0	64.8	33.33	44.46
26	83.3	67.4	41.33	61.48
27	86.5	70.5	56.00	68.45
28	86.8	65.7	37.22	55.90
29	83.5	66.2	37.22	42.95
30	82.1	64.0	30.00	36.46
Total or mean	80.5	65.0	343.43	421.62
Monthly total or mean	79.75	62.8	861.88	1,208.15

ENGELMANN SPRUCE ZONE

Date	Daily temperature: Maximum	Daily temperature: Mean	Physiological efficiency: Based on mean daily temperature	Physiological efficiency: Based on temperature by 2-hour periods
June 1	50.0	42.4	1.67	1.74
2	58.0	49.5	6.33	5.29
3	58.5	50.2	6.33	5.75
4	61.1	50.5	6.33	6.74
5	60.0	52.6	9.22	7.62
6	59.5	51.8	8.17	6.94
7	59.9	53.0	9.22	7.39
8	57.0	50.1	6.33	5.73
9	62.0	55.4	11.67	11.55
10	68.0	59.6	19.88	16.94
Total or mean	59.4	51.5	85.15	75.69
June 11	71.1	62.7	27.11	24.94
12	72.4	60.2	19.88	15.91
13	65.8	57.9	16.11	13.44
14	63.0	53.5	10.33	11.02
15	63.0	52.7	9.22	7.87
16	63.0	54.0	10.33	8.43
17	63.8	55.9	12.78	10.44
18	65.0	56.0	12.78	10.48
June 19	59.0	53.5	10.33	8.62
20	62.0	54.5	10.33	13.13
Total or mean	64.8	56.1	139.20	124.28
June 21	57.0	51.5	8.17	7.10
22	53.8	48.4	4.78	4.88
23	55.0	49.5	6.33	4.42
24	59.2	51.8	8.17	8.31
25	61.0	55.0	11.67	10.49
26	70.8	61.6	24.33	25.95
27	70.8	63.9	30.00	28.23
28	71.1	62.4	24.33	22.26
29	66.0	58.0	16.11	13.42
30	61.3	55.6	12.78	10.66
Total or mean	62.6	55.8	146.67	135.72
Monthly total or mean	62.3	54.45	371.02	335.69

Tables 9, 10, and 11 give temperature summations by different methods and for different periods in the five forest types, as does also Figure 18. The records necessary for these summations are available for the highest forest types only in the series of stations in the San Francisco Mountains. Physiological temperature efficiencies were computed by 2-hour periods. The duration of various temperatures was taken directly from the thermograph sheets, by simply determining the number of hours the graph was above or below any designated temperature line. A refinement of this scheme, which may be called the area method, measures by means of a planimeter the actual area lying between the temperature graph and any designated line on the thermograph sheet. In the last column of Table 11 is given the area or product of intensity by duration above the 42° F. line. Summations have also been made for longer intervals than June to September because they furnish a more complete expression of effective temperature conditions during a possible growing season.

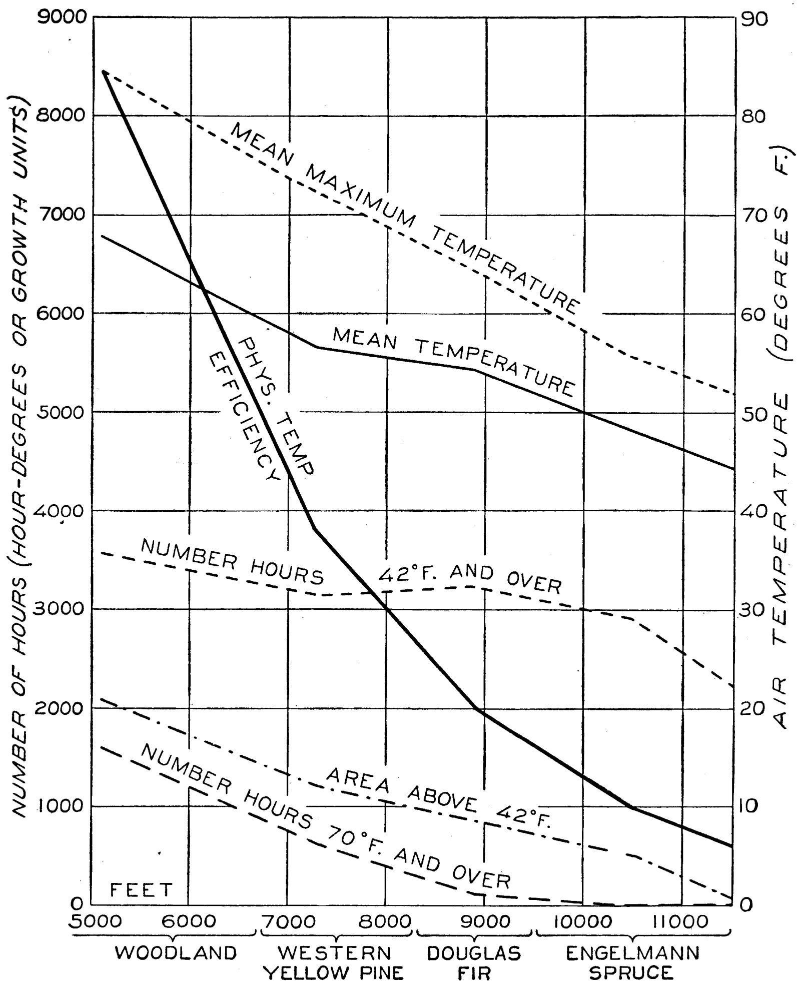

FIGURE 18.—Temperature summations by various methods in the San Francisco Mountains, May–September, 1918

When May is included, as in Table 9 (column 8) and in Figure 19, the seasonal physiological efficiency is increased substantially in the piñon-juniper type and considerably in the western yellow pine type, but increasingly less as altitude increases, until it becomes negligible when the Engelmann spruce type is reached. Table 10, which includes both May and October, shows the same relation with respect to the duration of temperatures above 42° but in less degree with respect to temperatures above 70°.

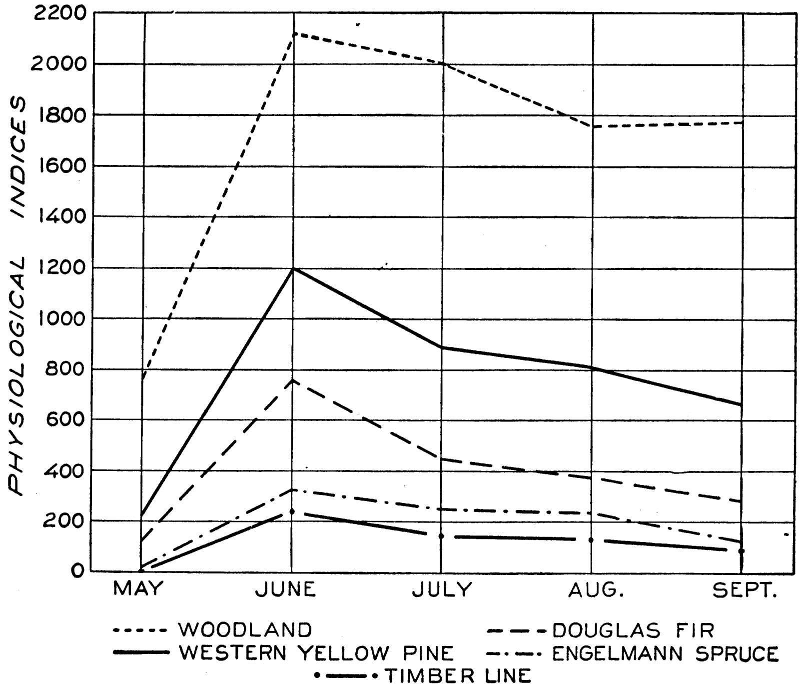

FIGURE 19.—Physiological temperature efficiency by forest types, San Francisco Mountains, 1918

TABLE 9.—*Physiological temperature efficiency by 10-day periods, based on 2-hour means from thermograph, northern Arizona, 1918*

Forest type	10-day period	May	June	July	Aug.	Sept.	Total May–Sept.	Total June–Sept.
Woodland (piñon-juniper)	1	269.0	655.5	598.2	578.6	602.0		
	2	248.0	698.3	597.6	422.4	644.4		
	3	247.5	759.2	808.4	761.2	522.1		
Total		764.5	2,113.0	2,004.2	1,762.2	1,768.5	8,412.4	7,647.9
Western yellow pine	1	74.9	379.4	273.2	254.9	171.3		
	2	76.5	407.2	239.6	183.0	308.8		
	3	83.6	421.6	380.9	378.5	188.1		
Total		235.0	1,208.2	893.7	816.4	668.2	3,821.5	3,586.5
Douglas fir	1	37.6	254.9	122.9	135.0	74.8		
	2	46.0	262.8	117.8	83.2	132.8		
	3	50.5	245.9	206.9	160.7	76.0		
Total		134.1	763.6	447.6	378.9	283.6	2,007.8	1,873.7
Engelmann spruce (northwest slope)	1	6.1	75.7	66.1	90.4	36.9		
	2	6.9	124.3	64.4	43.2	54.7		
	3	8.6	135.7	129.1	[1] 116.0	[1] 36.0		
Total		21.6	335.7	259.6	249.6	127.6	994.1	972.5
Timber line (ridge)	1	5.4	59.8	34.1	42.4	17.0		
	2	2.4	[1] 86.0	37.9	13.9	49.6		
	3	3.7	[1] 104.0	73.8	81.5	18.9		
Total		11.5	249.8	145.9	137.8	85.5	630.5	619.0

[1] Interpolated.

TABLE 10.—*Duration of various temperatures in northern Arizona, 1918*

Forest type	Hours during June to September at—				Hours during May to October at—				Hours during November to April at—			
	32° F. or less	Less than 42° F.	42° F. or more	70° F. or more	32° F. or less	Less than 42° F.	42° F. or more	70° F. or more	32° F. or less	Less than 42° F.	42° F. or more	70° F. or more
Woodland	0	5	2,923	1,489	16	240	4,176	1,829	(1)	(1)	(1)	(1)
Western yellow pine	21	203	2,725	633	287	860	3,566	657	2,191	3,152	1,192	0
Douglas fir	0	62	2,866	134	158	766	3,650	134	2,111	3,726	618	0
Engelmann spruce	0	150	2,778	4	462	1,205	3,211	4	3,172	4,168	176	0
Timber line	24	753	2,175	1	779	2,092	2,324	1	(1)	(1)	(1)	(1)

[1] No record.

TABLE 11.—*Temperature summations by different methods for five forest types in northern Arizona, May to September, inclusive, 1918*

Forest type	Mean temperature	Mean maximum temperature	Duration, 42° F. and above	Duration, 70° F. and above	Physiological temperature efficiency	Product of intensity by duration [1] above 42° F.
	°F.	*°F.*	*Hours*	*Hours*		
Woodland	68.1	84.4	3,577	1,629	8,412	2,089.2
Western yellow pine	56.5	72.2	3,155	633	3,822	1,206.6
Douglas fir	54.3	64.7	3,231	134	2,008	863.4
Engelmann spruce	48.3	55.9	2,922	4	994	511.8
Timber line	44.4	51.9	2,212	1	630	321.9

[1] Area described by the thermograph above the 42° line obtained by planimeter.

SOIL TEMPERATURE

Soil temperature has received relatively little attention as compared with air temperature and moisture. Records are not available over extensive regions, as they are for air temperature and precipitation. Though little is known regarding the effects of soil temperature upon plant life, that it must exert a considerable influence, within certain limits at least, is obvious. Plants can not absorb moisture from a soil that is frozen. Frozen soil associated with a dry atmosphere is thought to be a common cause of winterkilling. Observations of western yellow pine seedlings have shown that root growth does not begin until the temperature of the soil in the afternoons reaches a point well above 40° F. It is known that root growth in this and other species begins earlier in the spring than does the growth of aerial portions of the tree. It is also known that the temperature of the soil has a considerable influence upon chemical action and the activity of soil organisms.

In this study measurements of soil temperature were confined to the San Francisco Mountains and vicinity. Records in the piñon-juniper type cover only a single growing season, but those in the western yellow pine, Douglas fir, and Engelmann spruce types extend over three or more years. These records are presented in Table 12.

TABLE 12.—*Mean soil temperature by months at different depths by forest types, San Francisco Mountains*

1918 RECORDS

Depth and forest type	Station No.	Altitude	Shade	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Annual	June–Sept.
		Feet	*Per cent*	°*F.*	°*F.*	°*F.*	°*F.*	°*F.*	°*F.*	°*F.*	°*F.*	°*F.*	°*F.*	°*F.*	°*F.*	°*F.*	°*F.*
6 inches:																	
Western yellow pine	1A	7,300	25	28.5	28.4	35.8	42.8	50.5	63.4	62.4	62.6	60.3	51.8	37.5	30.7	46.2	62.2
Douglas fir	8A	8,900	60	31.7	29.7	32.1	34.1	43.4	55.2	53.8	52.7	48.7	42.4	33.4	31.0	40.7	52.6
Engelmann spruce	10A	10,500	90	------	------	------	------	------	41.2	45.6	45.0	42.7	37.5	------	------	------	43.6
12 inches:																	
Piñon-juniper	3	5,100	0	[1]40.0	[1]38.0	46.8	56.0	63.7	[1]73.0	[1]75.0	75.4	75.3	64.8	------	------	------	------
Western yellow pine	1C	7,300	0	33.5	31.1	35.6	46.7	56.6	65.4	65.3	65.9	63.6	[1]58.0	41.1	32.7	49.6	65.0
Do	1A	7,300	25	32.1	30.4	35.2	41.6	47.9	58.6	60.2	60.3	58.0	51.9	39.2	32.7	45.7	59.3
Do	1B	7,300	60	31.4	29.9	34.3	39.6	44.4	56.1	58.4	57.4	54.4	[1]48.0	37.3	33.1	43.7	56.6
Douglas fir	8A	8,900	60	32.4	30.9	32.4	33.7	41.3	53.0	53.5	52.2	48.7	44.0	35.3	32.7	40.8	51.8
Engelmann spruce	10A	10,500	90	28.3	28.0	29.7	30.6	31.6	39.4	45.5	45.3	43.4	39.3	31.8	30.0	35.2	43.4
Timber line	11A	11,500	0	------	------	------	------	------	39.3	47.1	47.5	46.4	41.1	31.5	------	------	45.1
24 inches:																	
Western yellow pine	1C	7,300	0	[1]35.5	[1]33.0	36.6	45.2	54.1	62.5	63.6	64.6	63.2	[1]59.5	43.7	36.8	49.9	63.5
Do	1A	7,300	25	34.8	32.2	35.3	40.0	46.3	53.8	58.2	58.3	57.4	53.9	41.6	36.5	45.7	56.9
Do	1B	7,300	60	33.6	32.5	35.2	39.6	49.1	52.7	56.7	57.2	55.7	50.0	40.3	35.6	44.8	55.6
Douglas fir	8A	8,900	60	33.8	31.9	32.8	33.6	40.1	49.7	52.0	51.6	48.8	44.5	37.1	34.4	40.9	50.5
Engelmann spruce	10A	10,500	90	30.1	29.3	30.2	30.8	31.6	35.7	43.3	44.4	43.3	40.3	33.8	31.1	35.3	41.7

1919 RECORDS

Depth and forest type	Station No.	Altitude	Shade	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Annual	June–Sept.
12 inches:																	
Western yellow pine	1C	7,300	0	30.2	29.9	33.0	44.0	56.6	64.4	65.3	65.8	63.1	48.4	38.5	35.0	47.8	64.6
Do	1A	7,300	25	27.5	28.7	31.0	38.9	47.7	56.1	60.3	60.1	58.0	46.2	37.0	34.1	43.8	58.6
Do	1B	7,300	60	29.7	30.5	31.2	37.9	46.2	53.6	59.2	58.7	55.6	44.2	37.3	34.8	43.2	56.8
Western yellow pine (upper limit)	8C	8,800	0	32.8	32.3	33.0	36.6	42.9	54.7	57.6	57.5	55.9	42.5	36.4	35.2	43.1	56.4
Douglas fir (aspen)	8B	8,900	40	32.3	32.1	32.2	34.1	45.4	51.1	54.6	55.4	53.2	42.1	35.7	34.3	41.9	53.6
Douglas fir	8A	8,900	60	30.5	30.5	30.9	32.6	42.7	52.1	53.4	53.6	49.6	39.1	34.3	34.0	40.3	52.2
Limber pine-bristlecone pine	9	10,000	0	28.9	33.2	29.3	35.0	45.7	55.1	55.8	54.6	53.7	41.6	36.4	34.3	42.0	54.8
Engelmann spruce (northwest slope)	10A	10,500	90	26.9	27.9	28.3	30.7	32.6	40.8	46.9	46.9	44.8	34.9	32.5	32.3	35.5	44.8
Engelmann spruce (ridge)	10B	10,500	25	32.4	30.9	31.7	32.1	38.1	52.1	52.8	56.4	50.9	38.2	33.8	32.9	40.2	53.0
Timber line (ridge)	11A	11,500	0	------	------	------	------	33.0	39.8	46.6	49.1	46.4	35.5	------	------	------	45.5
Timber line (northwest slope)	11B	11,500	0	------	------	------	------	32.1	41.2	45.9	46.4	43.0	33.1	------	------	------	44.1

AVERAGE FOR 1917 TO 1919, INCLUSIVE

12 inches:																
Western yellow pine	1A	7,300	25	30.4	30.0	32.7	38.8	47.8	57.4	60.2	60.2	58.0	49.9	39.2	34.0	44.9	59.0
Do	1B	7,300	60	30.7	30.3	32.3	37.3	43.8	54.1	58.7	58.1	55.3	47.1	38.2	34.1	43.3	56.6
Douglas fir	8A	8,900	60	31.0	30.5	31.2	32.8	39.9	51.1	53.4	52.8	48.9	42.1	35.9	33.6	40.3	51.6
Engelmann spruce	10A	10,500	90	28.2	28.4	29.0	30.7	32.1	38.1	44.8	45.9	43.7	37.5	32.6	31.2	35.2	43.1
24 inches:																
Western yellow pine [2]	1A	7,300	25	33.2	31.6	33.6	38.6	45.5	52.8	58.2	58.4	57.5	51.5	40.7	36.4	44.8	56.7
Do.[3]	1B	7,300	60	33.1	32.4	33.2	37.0	44.7	50.9	56.3	57.1	55.6	49.7	40.6	36.1	43.9	55.0
Douglas fir	8A	8,900	60	32.8	32.0	31.9	32.9	38.2	47.4	51.9	51.9	48.9	43.1	37.6	35.0	40.3	50.0
Engelmann spruce	10A	10,500	90	29.8	29.3	29.7	31.0	31.8	35.1	42.1	44.5	43.6	38.9	34.4	32.3	35.2	41.3

1913 RECORDS

24 inches:																
Western yellow pine (forest)	1B	7,300	60					41.7	49.2	54.8							
Western yellow pine (park)		7,250	0					52.1	61.1	65.9							

[1] Interpolated.
[2] 1918 and 1919 only.
[3] Incomplete 1919.

Relation Between Air and Soil Temperature

Soil temperature bears a fairly consistent relation to air temperature when the two are compared over rather long periods, but current variations often do not agree. For depths below about 6 inches, diurnal fluctuations in the soil are often directly contrary to those of the air because several hours are required to transmit surface change to the lower soil strata. Except in a thin surface layer, the temperature of the soil is much more constant than that of the air. Diurnal variations in soil and air temperature, according to thermograph records, are shown in Figure 20.

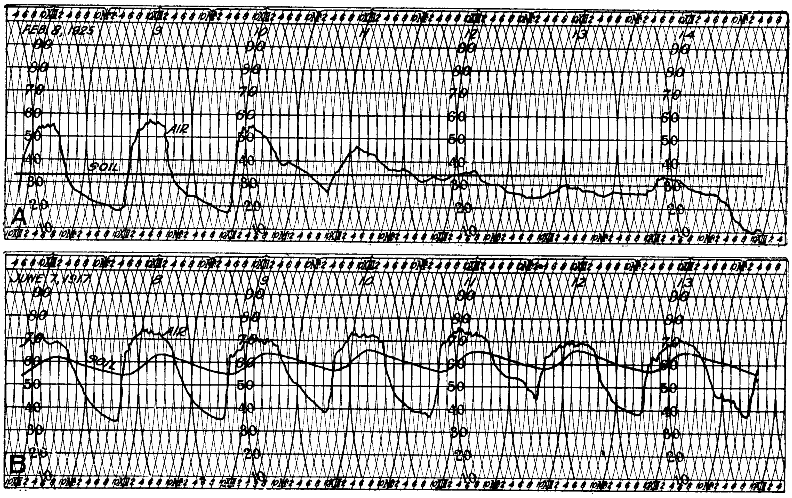

FIGURE 20.—Thermograph records of air temperature 8 feet above and soil temperature 6 inches below ground surface, western yellow pine type, Fort Valley, Ariz.: A, In winter, snow 6 inches deep, February 8–10 clear, February 11–15 cloudy; B, in summer

Effect of Cover, Slope, and Aspect

Soil temperature is influenced by both air temperature and the intensity and duration of direct solar radiation. As a medium for absorbing and retaining heat, the soil surpasses the air. Where exposed to the sun it is usually warmer than the air at the surface and not infrequently considerably below the surface. This is also usually the case in the fall when a deep blanket of snow covers the ground before it becomes deeply frozen. In the western yellow pine type, however, the mean temperature curve for the air falls below the soil curve long before the arrival of snow. (Fig. 21.)

Whenever cloudy skies or mechanical obstructions cut off a considerable proportion of the solar radiation the effect is reflected in the lowering of soil temperature. The effect of shade cast by tree crowns in lowering soil temperature is strikingly illustrated in Table 12 and Figure 22. Direction and steepness of slope are other important modifying factors. Southerly aspects are always warmer than northerly ones of the same gradient, and a steep slope of southerly exposure is warmer than a gentle or moderate one.

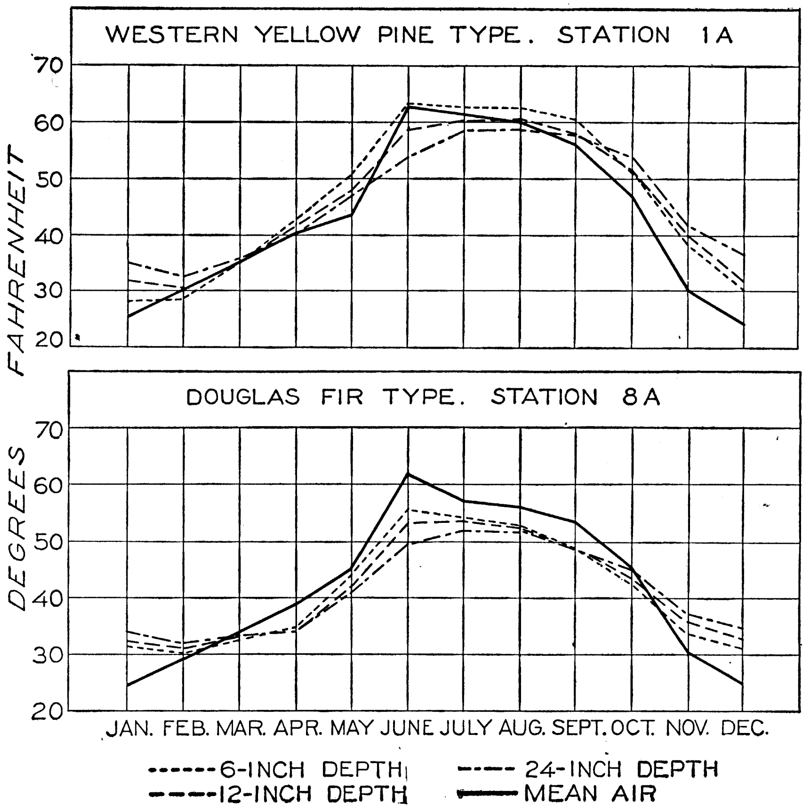

FIGURE 21.—Soil temperature at different depths in the western yellow pine and Douglas fir types, San Francisco Mountains, 1918

Making due allowance for the effects of cover and slope, it is evident that soil temperature decreases with a rise in altitude, as is shown in Table 12 and Figure 22 and especially by a comparison of the graphs for western yellow pine, Engelmann spruce, and timber

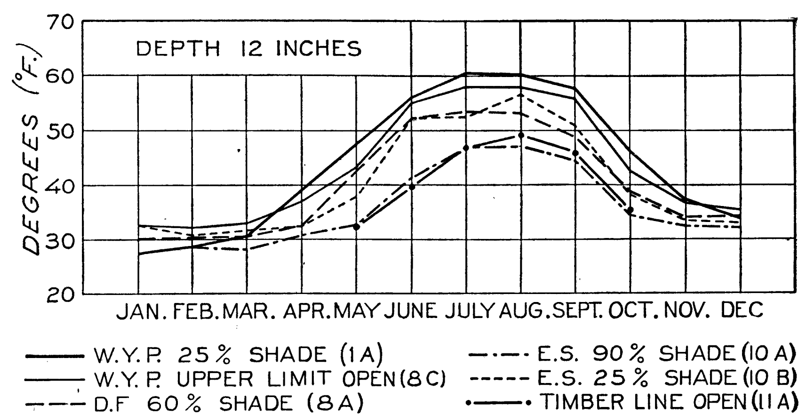

FIGURE 22.—Soil temperature in different forest types and degrees of shade, San Francisco Mountains, 1919

line. The last two stations had a slight advantage over the western yellow pine in aspect, and the timber-line station had less cover and so was more exposed than either of the others.

DURATION OF FREEZING TEMPERATURES

The duration of temperatures below freezing is an indication of the possibility of winterkilling. Although the monthly averages do not show what fluctuations may occur, it is known that for depths of a foot or more the fluctuations in January and February, and usually in March, are negligible. No winter records are available for the woodland type, but, judging by the temperatures in March,

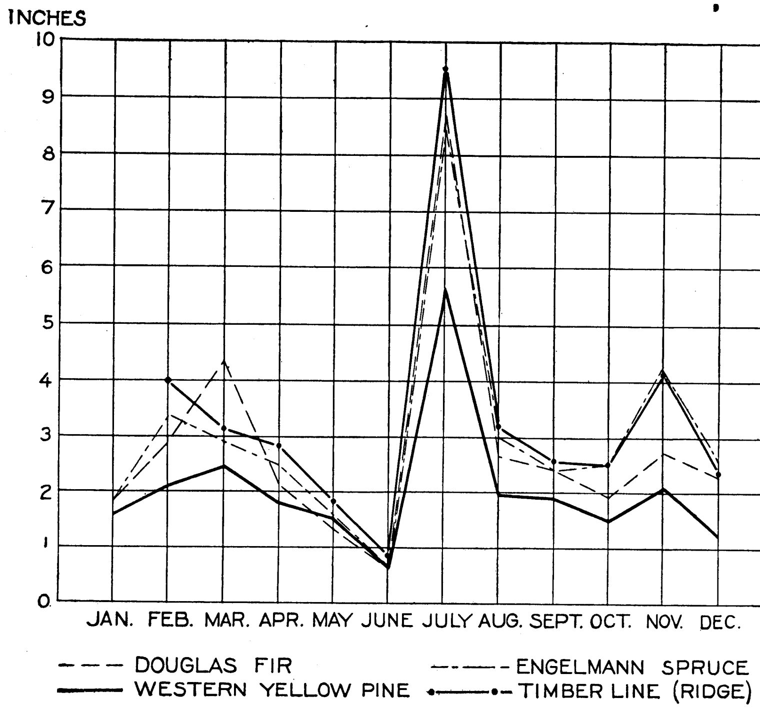

FIGURE 23.—Precipitation by forest types in the San Francisco Mountains, 1917–1919, inclusive

it appears unlikely that the soil remains frozen continuously during long periods. In the western yellow pine type, particularly in shaded situations, continuous records below 32° F. are the rule in January and February, in the Douglas fir type through the month of March, and in the Engelmann spruce type through both March and April.

PRECIPITATION

Moisture promotes plant growth only to the extent that it is available in adequate quantities when needed. Along with precipitation it is necessary to consider run-off, evaporation, and moisture content of the soil. Unfortunately precipitation is the only one of

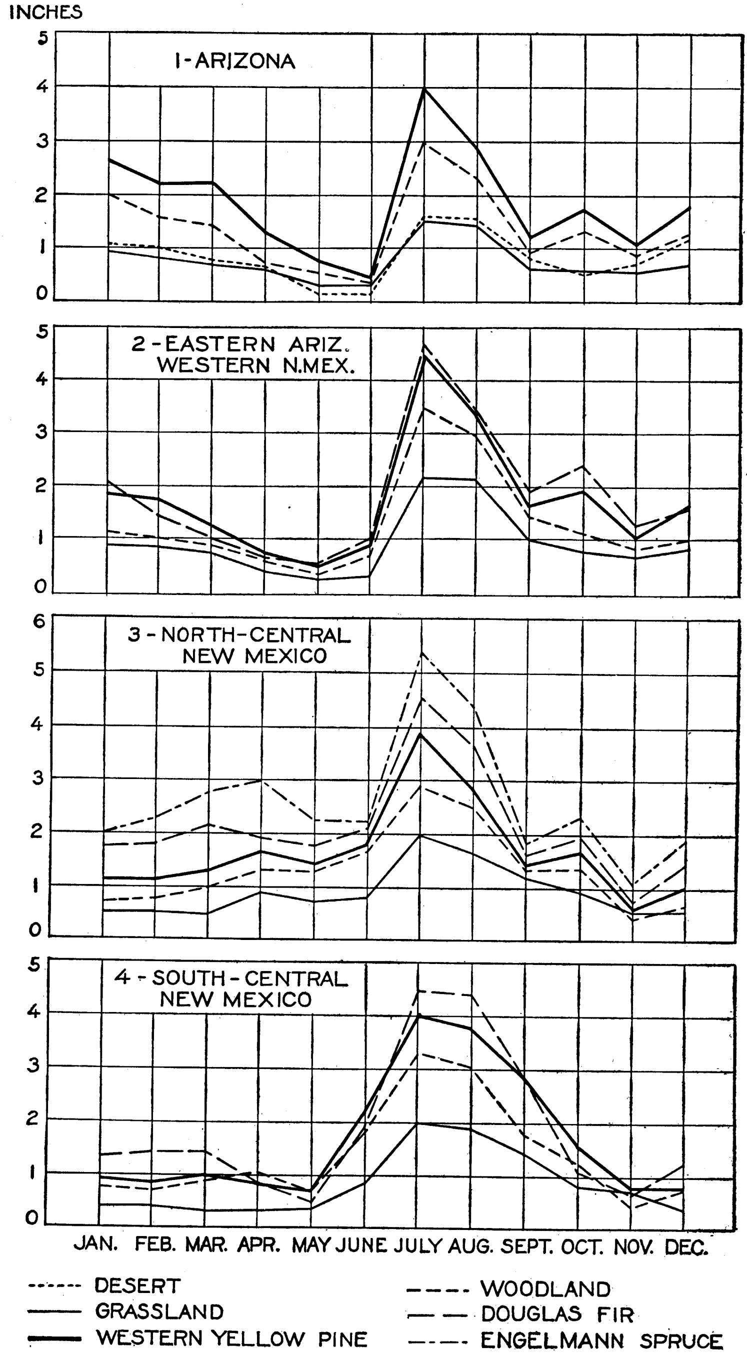

FIGURE 24.—Precipitation in different forest types grouped by regions, 1909–1921, with exceptions as noted in Table 14

these factors which has been measured in anything like a systematic manner over extensive territory. Only in the San Francisco Mountains have the other elements been adequately measured.

Although precipitation records do not tell the whole story, they give the most essential facts, especially when they are sufficiently detailed to show the intensity and frequency of individual storms, the proportion of clear and cloudy days, and the seasonal distribution of precipitation.

AMOUNT AND DISTRIBUTION OF PRECIPITATION BY TYPES

It is a common observation in mountain regions that precipitation increases with altitude. In the Southwest this rule holds with uniform consistency, when applied to a series of stations in the same locality over a period of years. (Tables 13 and 14 and figs. 23 and 24.) Although the seasonal apportionment is not the same in different localities, there is a consistent agreement in the average annual quantity of rainfall in a given type anywhere in the two States. Where marked discrepancies occur, they can usually be explained. As with temperature, there is a fairly definite range of precipitation within each forest type, stations situated near the lower limits usually showing less than those situated near the upper limits.

TABLE 13.—*Yearly variation in precipitation in inches in six forest types of northern Arizona (San Francisco Mountains), 1917–1919*

Forest type, station, and altitude	Precipitation, annual			Precipitation, May–September		
	1917	1918	1919	1917	1918	1919
	Inches	*Inches*	*Inches*	*Inches*	*Inches*	*Inches*
Woodland (piñon-juniper), Ash Fork, 5,100 feet	[1] 13.39	12.36	18.46	8.47	5.35	11.32
Western yellow pine:						
Fort Valley, 7,300 feet	18.18	23.58	32.03	8.79	9.15	17.47
Flagstaff, 6,900 feet	18.82	21.29	28.28	9.57	10.07	13.77
Douglas fir, 8,700 feet	23.60	35.76	43.23	13.31	12.97	21.52
Limber pine—bristlecone pine, 10,000 feet	----	----	----	----	----	21.29
Engelmann spruce, 10,500 feet	24.34	33.02	51.92	12.74	12.86	23.11
Timber line, 11,500 feet	28.03	37.74	52.05	14.51	15.37	23.88

[1] Cedar Glade record used for January.

TABLE 14.—*Monthly and annual precipitation by vegetational zones and regions in Arizona and New Mexico*

Region No.	Location	Stations	Length range of record	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Total annual	May-Sept.
	DESERT																
		Number [1]	*Years* [2]	*Inches*	*Inches*	*Inches*	*Inches*	*Inches*	*Inches*	*Inches*	*Inches*	*Inches*	*Inches*	*Inches*	*Inches*	*Inches*	*Inches*
1	Arizona	5	19-52	1.12	1.00	0.78	0.62	0.14	0.15	1.65	1.60	0.83	0.53	0.75	1.23	10.40	4.37
	GRASSLAND																
1	Arizona	4	10-13	0.96	0.80	0.63	0.56	0.30	0.28	1.54	1.46	0.69	0.66	0.60	0.76	9.24	4.27
2	Eastern Arizona and western New Mexico	6	11-42	.91	.90	.74	.42	.27	.38	2.18	2.11	1.01	.82	.72	.90	11.36	5.95
3	North-central New Mexico	7	22-68	.52	.49	.51	.98	.81	.88	2.03	1.74	1.24	.98	.56	.58	11.32	6.70
4	South-central New Mexico	4	22-61	.44	.48	.35	.37	.40	.86	2.00	1.93	1.47	.91	.80	.49	10.50	6.66
	Average															10.60	5.90
	WOODLAND (PIÑON-JUNIPER TYPE)																
1	Arizona	9	6-13	1.97	1.58	1.42	0.75	0.55	0.37	3.09	2.35	0.97	1.42	0.91	1.32	16.70	7.33
2	Eastern Arizona and western New Mexico	14	10-48	1.14	1.03	.95	.61	.40	.72	3.55	3.04	1.47	1.20	.86	1.07	16.04	9.18
3	North-central New Mexico	8	10-13	.78	.85	1.01	1.37	1.32	1.76	2.94	2.52	1.35	1.41	.46	.72	16.49	9.89
4	South-central New Mexico	3	10-13	.80	.71	.91	1.06	.78	1.81	3.31	3.10	1.84	1.28	.49	.79	16.88	10.84
	Average															16.53	9.31
	WESTERN YELLOW PINE ZONE																
1	Arizona	3	13	2.61	2.20	2.22	1.33	0.77	0.46	4.02	2.90	1.29	1.86	1.14	1.87	22.67	9.44
2	Eastern Arizona and western New Mexico	6	9-13	1.89	1.75	1.25	.79	.56	.97	4.54	3.45	1.65	1.99	1.10	1.67	21.61	11.17
3	North-central New Mexico	11	6-13	1.18	1.14	1.32	1.72	1.44	1.85	3.90	2.91	1.44	1.71	.63	1.06	20.30	11.54
4	South-central New Mexico	4	6-13	.95	.89	1.00	.92	.77	2.20	4.00	3.86	2.89	1.62	.86	.87	20.83	13.72
	Average															21.35	11.47

TABLE 14.—*Monthly and annual precipitation by vegetational zones and regions in Arizona and New Mexico*—Continued

DOUGLAS FIR ZONE

Region No.	Location	Stations [1]	Length range of records	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Annual	June–Sept.
		Number [1]	*Years* [2]	*Inches*	*Inches*	*Inches*	*Inches*	*Inches*	*Inches*	*Inches*	*Inches*	*Inches*	*Inches*	*Inches*	*Inches*	*Inches*	*Inches*
1	Arizona [3]	1	3	1.85	2.96	4.39	2.12	1.38	0.66	8.83	2.68	2.38	1.94	2.77	2.24	34.20	15.93
2	Eastern Arizona and western New Mexico	2	6–10	2.10	1.48	1.07	.68	.67	1.02	4.76	3.52	1.96	2.48	1.30	1.62	22.66	11.93
3	North-central New Mexico	7	12–13	1.80	1.84	2.20	1.99	1.85	2.13	4.67	3.70	1.65	2.00	.83	1.43	26.09	14.00
4	South-central New Mexico	1	13	1.34	1.46	1.44	.90	.49	1.95	4.48	4.43	2.87	1.16	.73	1.23	22.48	14.22
	Average															26.36	14.02

ENGELMANN SPRUCE ZONE

Region No.	Location	Stations [1]	Length range of records	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Annual	June–Sept.
1	Arizona [3]	1	3	1.86	3.48	2.90	2.48	1.63	0.65	8.52	3.02	2.41	2.60	4.36	2.51	36.42	16.23
3	North-central New Mexico	3	10–13	2.06	2.29	2.87	3.01	2.28	2.30	5.46	4.42	1.91	2.36	1.13	1.97	32.06	16.37
	Average															34.24	16.30

[1] In each zone and region the records from a number of stations at different altitudes have been averaged. With few exceptions, the shorter records fall within the period 1909–1921, inclusive.

[2] Minimum and maximum number of years of record.

[3] These records cover only three years, 1917–1919, and are about 9 per cent above the 1909–1921 normal.

The high altitudes of Arizona are represented only by records in the San Francisco Mountains during the 3-year period 1917–1919. Records at the control station in the western yellow pine type (Table 15) show that the average for this period was almost exactly 2 inches (9 per cent) above the average for 1909–1921. This excess was due to a very large excess in 1919, when the total was 9.41 inches (42 per cent) above the 1909–1921 average. At the control station the total for 1919 was 53 per cent above the average for 1917 and 1918, and at the Douglas fir, Engelmann spruce, and timber-line stations it was 46,[13] 81, and 58 per cent, respectively, above the 1917–18 average (Table 13). Because of the fairly consistent relationship between 1919 and the two previous years in all the forest types it seems safe to assume that the excess of 9 per cent in the western yellow pine type during the 1917–1919 period is at least a rough index of corresponding departures from normal in the other types. Accordingly, it is assumed that the average annual precipitation recorded at the Douglas fir, Engelmann spruce, and timber-line stations in region 1, as given in Table 14, should be reduced by approximately 9 per cent when compared with the 1909–1921 means given for other types and regions. This applies also to the growing-season totals, but because of the large current fluctuations which have been noted it is not considered advisable to apply correction factors to the monthly values.

TABLE 15.—*Monthly and annual precipitation at the control station (Fort Valley, Ariz.) western yellow pine zone, 1909–1925*

Year	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Annual
	Ins.	*Ins.*	*Ins.*	*Ins.*	*Ins.*	*Ins.*	*Ins.*	*Ins.*	*Ins.*	*Ins.*	*Ins.*	*Ins.*	*Ins.*
1909	2.88	3.19	2.68	0.50	0.28	0.71	2.50	3.44	1.80	0	1.50	3.10	22.58
1910	2.79	.39	3.22	.50	0	.50	1.88	3.40	.41	0.59	.88	.97	15.53
1911	2.76	2.72	2.64	.22	T.	.22	5.71	2.76	3.47	2.68	.22	.69	24.09
1912	.12	.14	5.43	1.48	.55	.67	3.70	.81	.06	4.43	.25	.88	18.52
1913	.95	3.56	1.28	.09	T.	.16	2.16	4.44	1.87	1.26	1.88	1.47	19.12
1914	2.29	.86	.48	.74	.84	1.22	3.76	2.66	.89	1.84	T.	2.23	17.81
1915	3.19	2.95	.95	4.35	2.15	.35	2.92	.67	.54	.29	1.35	4.45	24.16
1916	8.57	.82	2.69	.30	.35	0	3.54	3.87	2.01	3.82	0	1.15	27.12
1917	2.98	1.43	.58	4.40	1.13	.02	5.10	.92	1.62	T.	T.	T.	18.18
1918	2.01	2.13	5.19	.31	T.	1.96	3.67	2.64	.88	.60	1.58	2.61	23.58
1919	T.	2.75	1.68	.68	3.54	T.	8.39	2.32	3.22	3.91	4.56	.98	32.03
1920	1.85	6.44	3.09	1.10	1.13	.08	2.00	2.38	.91	2.94	.97	1.02	23.91
1921	2.70	.47	1.49	1.47	2.37	.83	4.93	4.67	.19	3.13	.65	4.52	27.42
1922	4.45	1.85	3.11	1.54	1.23	1.31	1.16	2.53	1.40	1.63	2.64	1.87	24.72
1923	2.59	2.30	2.35	.93	.33	0	4.03	2.70	4.49	.32	2.66	4.39	27.09
1924	T.	.09	2.92	2.27	.09	.21	3.34	.20	3.15	1.52	.73	4.48	19.00
1925	.13	1.00	1.77	2.07	0	1.18	1.77	3.72	3.37	2.38	1.53	.11	19.03
Average	2.37	1.95	2.44	1.35	.82	.55	3.56	2.60	1.78	1.84	1.26	2.05	22.58

T.=trace.

Because it seems impractical to reduce the monthly values to a norm, the Douglas fir, Engelmann spruce, and timber-line graphs have been omitted from the Arizona series in Figure 24, and a supplementary set of graphs based entirely on 1917–1919 records is presented in Figure 23. Except for the winter and spring months, the graphs in Figure 23 are fairly harmonious when one considers the usual erratic character of precipitation. The irregularities during the winter months are probably due in part to mechanical dif-

[13] This figure is out of line because of the high precipitation recorded at the Douglas fir station in 1918. See Table 13.

ficulties in obtaining an accurate measure of snow water. Some of the most conspicuous cases, however, are accounted for by abnormal storms. An example is the high point in the Douglas fir graph in March. This is known to be the result of a tremendous local downpour of rain between March 1 and March 13, 1918, when the catch at the Douglas fir station amounted to 10.20 inches, whereas in the western yellow pine type it was 5.19 inches, and in the Engelmann spruce type it was 4.64 inches.

Table 13 shows the variations from year to year in the total annual and summer precipitation in the San Francisco Mountain region. With a few exceptions, notably in the piñon-juniper type, both the annual and the summer precipitation rise by fairly regular steps from 1917 to 1919. The increase with elevation is rapid from the piñon-juniper type to the Douglas fir type. This holds for each individual year as well as for the average and, with one exception, for the summer as well as the yearly total. Above the Douglas fir type the average rate of increase with altitude falls off, although there is still a perceptible increase up to timber line. Evidently the elevation of timber line in the San Francisco Mountains (11,500 feet) is not sufficient to record the definite decrease in precipitation that Visher (*46*) finds to be the rule above moderate heights.

The transition from grassland to woodland is accompanied by a rise in precipitation to 16 inches and more. At some stations in the lower edge of the woodland the annual catch is as low as 12 inches, whereas in the upper edge it may be as high as 20 inches. A comparison of the four regions in Table 14 shows an average variation in annual precipitation in the woodland of less than 1 inch. This, like the succeeding forest types, represents a well-defined vegetational unit in which it is reasonable to expect a rather narrow range of climatic conditions.

In the western yellow pine zone a distinct increase in precipitation is shown along with the rise in altitude over the piñon-juniper type. Of the four regions, Arizona (region 1) has the highest annual total precipitation and north-central New Mexico the lowest. The relatively low average for north-central New Mexico and for New Mexico in general may be attributed mainly to better seasonal distribution, because of greater rainfall during May and June, which would permit western yellow pine to grow with a lower annual precipitation than is required in Arizona.

Available Douglas fir records indicate a generally greater abundance of moisture than is shown by records for the western yellow pine zone. In north-central New Mexico, the only region in which there are sufficient stations and sufficiently long records to establish a good average, the Douglas fir type shows an annual excess of nearly 6 inches over the western yellow pine type for the same region. In northern Arizona, where the Douglas fir records, though at a typical station, cover only three years, the excess is 11.5 inches. In regions 2 and 4 the margin in favor of the Douglas fir type is barely more than 1 inch. Here the occurrence of Douglas fir at the higher altitudes is accounted for less by increased precipitation than by decreased temperature, which renders a given amount of precipitation more effective. At Cloudcroft, the only Douglas fir station in south-central New Mexico (region 4), the Douglas fir type is confined largely to north exposures. At higher elevations in this locality, which probably combine higher precipitation with lower temperature, Douglas fir occupies all exposures.

The Engelmann spruce type is represented solely by three stations in north-central New Mexico and one in northern Arizona. In north-central New Mexico there is a substantial rise in precipitation as one ascends from the Douglas fir to the Engelmann spruce type. A smaller increase is indicated in the San Francisco Mountains of Arizona. In the latter region, however, the increase in precipitation in the Engelmann spruce type over that in the western yellow pine type is larger than in New Mexico.

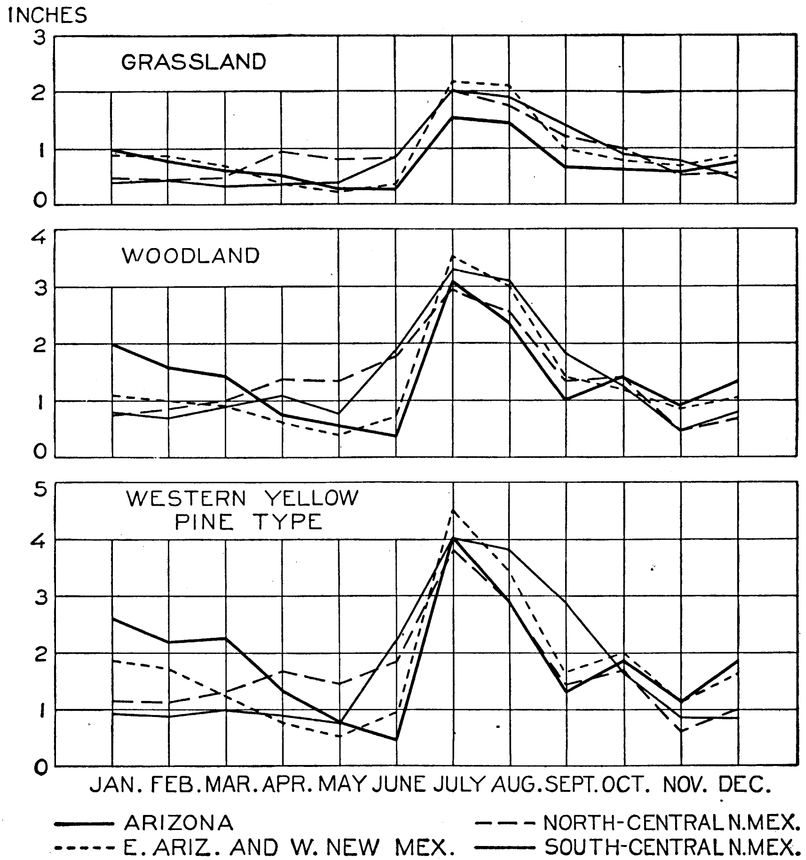

FIGURE 25.—Seasonal distribution of precipitation in regions 1 to 4, 1909–1921

Timber line, or the upper limit of the Engelmann spruce type, according to the San Francisco Mountain records (Table 13), appears to receive but slightly more precipitation than the Engelmann spruce type proper.

SEASONAL DISTRIBUTION OF PRECIPITATION

As has already been intimated, seasonal variations in precipitation are very similar at different altitudes within a given locality but are not the same when different regions are compared. This statement is amply illustrated in Figure 25 and Table 16. Arizona and New Mexico both have a pronounced rainy season in July and August, followed by a comparatively dry autumn; New Mexico has drier winters than Arizona, but Arizona has drier weather than New Mexico during the months of April, May, and June. These differences very nearly conform to the boundary line between the two States and are manifestations of a more or less gradual trend from west to east. From the Pacific coast eastward, the winter precipitation decreases, whereas that of spring and early summer increases. At Los Angeles 78 per cent of the annual precipitation occurs between December 1 and April 1, while less than 4 per cent is recorded in May and June, and only 0.2 per cent in July and August. At Prescott, Ariz., the corresponding percentages are 39, 4, and 34; at Fort Bayard, N. Mex., they are 22, 7, and 42; and at Fort Stanton, N. Mex., they are 17, 14, and 40. These differences are attributable to the fact that at the west end of the series the storms originate on the Pacific coast, at the east end they come mainly from the Gulf of Mexico, and between the two extremes they come from either source.

TABLE 16.—*Seasonal distribution of precipitation in different regions*[1]

Region No.	Location	Stations	Nov.-Mar.		Apr.-June		July-Aug.		Sept.-Oct.		Annual
		Number	*Inches*	*Per cent*	*Inches*	*Per cent*	*Inches*	*Per cent*	*Inches*	*Per cent*	*Inches*
	DESERT										
1	Arizona	5	4.88	47	0.91	9	3.25	31	1.36	13	10.40
	GRASSLAND										
1	Arizona	4	3.75	41	1.14	12	3.00	32	1.35	15	9.24
2	Eastern Arizona and western New Mexico	6	4.17	37	1.07	9	4.29	38	1.83	16	11.36
3	North-central New Mexico	7	2.66	23	2.67	24	3.77	33	2.22	20	11.32
4	South-central New Mexico	4	2.56	24	1.63	16	3.93	37	2.38	23	10.50
	WOODLAND										
1	Arizona	9	7.20	43	1.67	10	5.44	33	2.39	14	16.70
2	Eastern Arizona and western New Mexico	14	5.05	31	1.73	11	6.59	41	2.67	17	16.04
3	North-central New Mexico	8	3.82	23	4.45	27	5.46	33	2.76	17	16.49
4	South-central New Mexico	3	3.70	22	3.65	22	6.41	38	3.12	18	16.88
	WESTERN YELLOW PINE ZONE										
1	Arizona	3	10.04	44	2.56	11	6.92	31	3.15	14	22.67
2	Eastern Arizona and western New Mexico	6	7.66	35	2.32	11	7.99	37	3.64	17	21.61
3	North-central New Mexico	11	5.33	26	5.01	25	6.81	34	3.15	15	20.30
4	South-central New Mexico	4	4.57	22	3.89	19	7.86	38	4.51	21	20.83

[1] Records, with few exceptions, cover the period 1909–1921.

TABLE 16.—*Seasonal distribution of precipitation in different regions*—Continued

DOUGLAS FIR ZONE

Region No.	Location	Stations	Nov.-Mar.		Apr.-June		July-Aug.		Sept.-Oct.		Annual
		Number	*Inches*	*Per cent*	*Inches*	*Per cent*	*Inches*	*Per cent*	*Inches*	*Per cent*	*Inches*
1	Arizona [1]	1	14.21	41	4.16	12	11.51	34	4.32	13	34.20
2	Eastern Arizona and western New Mexico	2	7.57	33	2.37	10	8.28	37	4.44	20	22.66
3	North-central New Mexico	7	8.10	31	5.97	23	8.37	32	3.65	14	26.09
4	South-central New Mexico	1	6.20	27	3.34	15	8.91	40	4.03	18	22.48

ENGELMANN SPRUCE ZONE

Region No.	Location	Stations	Nov.-Mar.		Apr.-June		July-Aug.		Sept.-Oct.		Annual
1	Arizona [1]	1	15.11	41	4.76	13	11.54	32	5.01	14	36.42
3	North-central New Mexico	3	10.32	32	7.59	24	9.88	31	4.27	13	32.06

[1] Record covers only 3 years.

A strip extending roughly 50 miles west and 100 miles east of the Arizona-New Mexico State line (region 2) constitutes a transition zone in which conditions in any particular year may approach either of the two extremes but on an average are more like those prevailing farther west. It should be borne in mind that Figures 24 and 25 represent the average distribution over a period of 13 years. Any single year may prove an exception. Thus, it happens that May and June are not always dry in Arizona, nor are they always wet in New Mexico. This subject has been discussed by the writer in an earlier paper (*33*).

RUN-OFF

It is known that of the annual precipitation a very considerable proportion runs off the surface as flood water. No data are available for a direct, quantitative comparison of run-off in the various vegetational zones, but, by applying existing knowledge regarding precipitation, soil, ground cover, and forest cover, one can not escape the conclusion that the proportion of surface run-off is generally greater at the lower than at the higher altitudes. Soil cover more than any other factor accounts for this difference.

Despite an annual rainfall in the desert and grassland of only 9 to 12 inches, floods of such proportions as to endanger life and property are by no means uncommon. Ample evidence of such floods is furnished by the numerous deep arroyos and the débris which marks the high-water line of the larger streams. These conditions are readily understood when one considers that a drought of three months or more may be followed by a rainfall of 4 or 5 inches in a few days. Add to this a scanty cover of vegetation often associated with shallow, compact soil, and it becomes evident that the lower country in the Southwest furnishes ideal conditions for excessive run-off and erosion. These naturally unfavorable conditions are rendered infinitely worse by the overgrazing which is everywhere in evidence. Where the ground is occupied by trees, brush, or grass both run-off and erosion are greatly checked.

In the piñon-juniper type the soil is well protected by vegetation when natural conditions have not been violently disturbed. But on extensive areas the natural cover has been destroyed not only by overgrazing but also by timber cutting, fire, and cultivation. Here, where precipitation is much heavier, denudation approaches that of the grassland, and run-off is great. Sheet erosion removes the surface soil, cow trails and wagon roads are cut down to bedrock, and the creeks and larger arroyos carry away the soil from entire valleys.

The western yellow pine type in its virgin state is well adapted to conserving moisture. The crown canopy breaks the force of the rain and retards the melting of snow. Observations by Jaenicke (*21*) at the Southwestern Forest and Range Experiment Station have shown that in a western yellow pine forest snow usually lies from 10 days to two weeks longer than in a neighboring treeless park. Leaf litter 2 inches deep carpets the soil around the trees, and open spaces are occupied by a luxuriant growth of grass or young pines. Under these conditions there is little danger of surface run-off and erosion; but when man introduces lumbering, grazing, and fire, the situation rapidly changes, and the ground becomes bare, the slopes gullied, and the valleys channeled.

The Douglas fir and Engelmann spruce forests are the great storage reservoirs which feed the permanent springs and streams in the Southwest. Heavy precipitation, dense cover, and porous soils combine to create ideal conditions for water supply. Relatively little cutting has been done in these types, but fire has swept enormous areas, killing nearly all the trees. Many of these burns now support a good cover of young conifers or aspen. Where the soil cover has been destroyed by logging, fire, and grazing run-off and erosion may become worse than in the lower types because the precipitation is greater and the slopes are steeper. Properly regulated logging without fire will, however, cause little permanent erosion, since the young tree growth thus protected is usually sufficient to provide adequate soil cover.

WIND, HUMIDITY, AND EVAPORATION

Water that is evaporated directly from the soil is obviously lost to vegetation. Wind and high temperature increase evaporation, and atmospheric humidity decreases it. With a knowledge of these factors, it is possible to estimate evaporation to a certain extent. Evaporation is an important factor in the Southwest because atmospheric conditions there favor extremely high water loss both from leaf surface and from the soil direct.

Although an exact determination of evaporation by the formula method requires more exact measurements of physical factors than are usually available, an experienced observer with the aid of only meager records can tell whether the evaporation in a given place is likely to be high or low. An illustration of the interrelation between wind, relative humidity, rainfall, and evaporation is furnished by Figure 26.

Other things being equal, wind movement is greatest in the high altitudes, but even here it is greatly influenced by exposure. According to Table 17 the highest movement is recorded at the ridge station at timber line, but only 37 per cent as much is recorded at the more sheltered timber-line station on the northwest slope. The slope station, though only about 100 yards distant, is below the crest of the ridge to the north and is sheltered on the west side by a fairly dense stand of spruce. The prevailing wind in this region is from

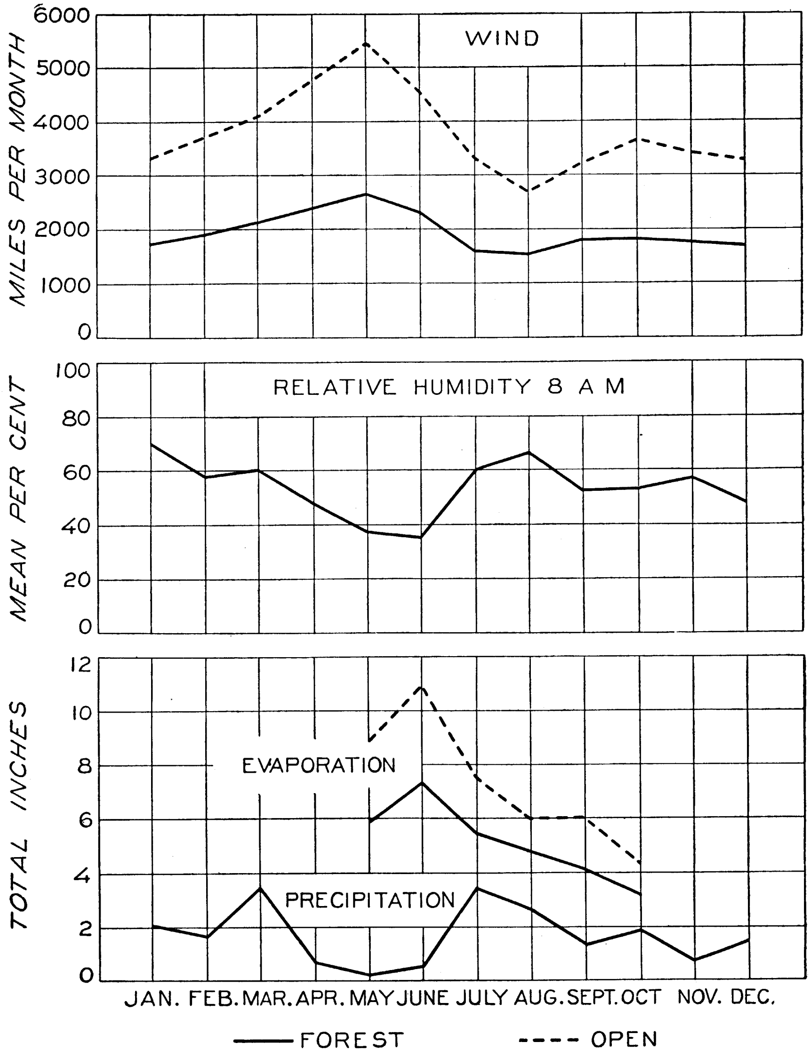

FIGURE 26.—Wind, humidity, evaporation, and precipitation at the control stations, western yellow pine type, Fort Valley, Ariz., 1909–1912, inclusive

the southwest, but at this station it is probably more nearly from the northwest. The Engelmann spruce station, also on a northwest slope, is surrounded by dense, tall timber. It records the least wind in the series and is probably typical of the better spruce and fir stands. At the limber pine-bristlecone pine station, situated only 500 feet lower but on an open southwest slope, the movement approaches that of the timber-line ridge. Again, in the western yellow pine type the effect of forest cover is evident. This is strongly brought out in Figure 26, where conditions in the virgin forest are compared with those in an open area or park about 1 mile in diameter.

TABLE 17.—*Daily average wind movement by forest types, San Francisco Mountains, 1918* [1]

Forest type	Exposure	Altitude	Station Number	Wind movement			
				July	Aug.	Sept.	Oct.
		Feet		*Miles*	*Miles*	*Miles*	*Miles*
Western yellow pine	Level, virgin forest	7,300	1A	50.0	51.0	56.2	58.1
Limber pine-bristlecone pine	Open, steep southwest slope.	10,000	9	163.0	170.1	199.9	
Engelmann spruce	Northwest slope, dense forest.	10,500	10A	36.1	39.3	37.0	45.3
Timber line (ridge)	Open, exposed all sides.	11,500	11A	195.7	198.8	248.7	246.1
Timber line (northwest slope)	Ridge on south, timber on west.	11,500	11B				91.0

[1] Anemometer 8 feet above the ground.

As is shown by Table 18 and Figure 26, April, May, and June are the windiest months of the year, with the maximum wind movement occurring in May. May and June are also the periods of lowest precipitation, lowest relative humidity, and highest evaporation.

Comparable humidity readings for a series of forest types have not been obtained. The best high-altitude records available in this region were made by E. L. Hamilton on Mount Graham. Readings were made daily at 8 a. m., 12 m., and 4 p. m. in the Douglas fir type at 8,700 feet, through May, June, and July, 1926. In the Douglas fir type the average relative humidities for May, June, and July were 50, 38, and 60 per cent; in the desert type at 2,900 feet elevation they were 26, 18, and 32 per cent. Daily averages for June, together with readings at the same hours in the desert type at Safford, Ariz., at the foot of the mountain, are given in Figure 27.

TABLE 18.—*Daily average wind movement at the control station (Fort Valley, Ariz.), western yellow pine type, by months, 1909–1919*

Year	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Average for year [1]	Average for May–Sept. [1]
	Miles	*Miles*	*Miles*	*Miles*	*Miles*	*Miles*	*Miles*	*Miles*	*Miles*	*Miles*	*Miles*	*Miles*		
1909	57.7	67.4	67.6	91.1	85.3	77.9	60.3	41.5	55.5	76.9	63.5	54.5	66.6	64.1
1910	58.4	67.2	64.4	74.5	80.5	81.7	62.4	49.9	62.1	63.4	47.7	54.3	63.9	67.3
1911	57.1	66.1	54.7	79.5	90.3	74.9	47.2	48.8	51.2	60.3	68.1	54.9	62.8	62.5
1912	57.2	67.7	67.4	78.0	83.1	71.4	53.8	55.7	68.3	57.6	56.9	61.6	64.9	66.5
1913	61.4	59.2	69.4	78.1	77.2	78.5	62.6	47.5	48.4	60.3	48.6	50.0	61.8	62.8
1914	51.8	60.3	68.0	74.2	61.8	69.0	41.8	41.8	57.6	55.8	51.2	44.0	56.4	54.4
1915	55.6	58.8	64.2	50.9	64.9	71.7	40.5	49.4	58.2	51.1	53.9	50.2	55.8	56.9
1916	59.7	45.6	66.5	67.1	89.7	82.6	41.6	46.9	50.3	66.2	62.5	70.6	62.4	62.2
1917	52.1	65.2	69.6	60.9	78.2	72.4	53.9	54.1	53.8	58.5	59.4	61.2	61.6	62.5
1918	62.8	64.4	71.1	84.4	76.6	61.4	50.0	51.0	56.2	58.2	64.0	54.4	62.9	59.0
1919	53.7	68.3	65.9	72.1	66.0	67.0	42.9	42.6	46.2	56.1	62.1	57.8	58.4	52.9
Average	57.0	62.7	66.3	73.7	77.6	73.5	50.6	48.1	55.3	60.4	58.0	55.8	61.6	61.0

[1] These averages are not absolutely correct, because they give equal weight to all months regardless of the number of days.

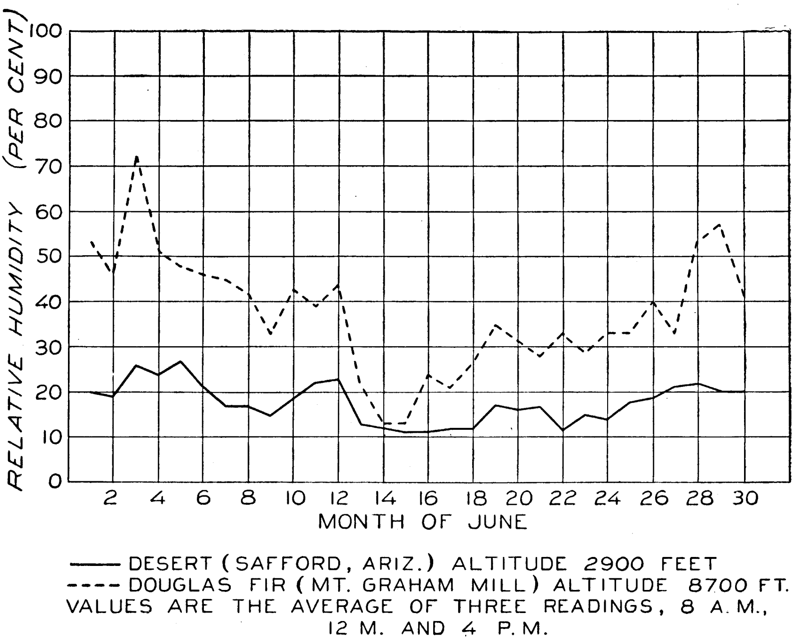

FIGURE 27.—Daily relative humidity in desert and Douglas fir type, June, 1926

Records kept at the Fort Valley forest station from May to October, 1925, reveal a low relative humidity during the month of June of 1 per cent. Records for other years show that values below 5 per cent are not uncommon during this month.

TABLE 19.—*Average evaporation and precipitation in different types in Arizona, June to September, 1918 and 1919, and average 1917–1919*

Forest type, station, and altitude	Evaporation from water surface			Precipitation	P/E [1]
	1918	1919	Average, 1917–1919		
Grassland:	*Inches*	*Inches*	*Inches*	*Inches*	
Wilcox, Ariz	37.31	37.29	39.62	5.97	0.151
Woodland (piñon-juniper):					
Ash Fork (open), 5,100 feet	41.95				
Western yellow pine:					
Fort Valley (forest), 7,300 feet	18.43	15.40	18.63	10.25	.550
Walnut Canyon (forest), 6,700 feet	27.12				
Douglas fir, 8,900 feet:					
Timber	15.40	11.96	15.48		
Aspen	14.69	10.77			
Average	15.04	11.36	14.86	14.55	.979
Limber pine-bristlecone pine, 10,000 feet:					
Steep southwest slope (open)		22.73			
Engelmann spruce, 10,500 feet:					
Northwest slope (forest)	6.05				
Northwest slope (open)		9.34			
Ridge (open)	16.27	14.06			
Average	11.15	11.70	10.49	14.60	1.392
Timber line, 11,500 feet:					
Ridge (open)	20.42	19.18		16.07	[2].812

[1] Precipitation divided by evaporation.
[2] Evaporation 2 years only.

Table 19 gives evaporation records in several vegetational zones during the four summer months, June to September, of the years 1917 to 1919. The records are not sufficiently complete to afford a comparison of all stations during the entire period. Each station, however, is represented in either 1918 or 1919, and therefore the data for these two years are entered separately in columns 2 and 3.

As may be seen from Table 19, evaporation decreases generally as one ascends from the lower and warmer to the higher and colder vegetational zones. A notable exception is the timber-line station, which shows a greater water loss than the stations in the western yellow pine, Douglas fir, and Engelmann spruce types. The limber pine-bristlecone pine station, though at an altitude of 10,000 feet, holds the record for all stations above the grassland. In both instances the high rate of evaporation is due primarily to extremely high wind movement. Other conditions being the same, the highest rate of evaporation occurs in the low altitudes, because of high temperatures and low humidity; on southern exposures, because of accessibility to sun and wind; and in open, as compared with forested situations, again because of the effects of sun and wind.

Table 20 gives the monthly and yearly evaporation during the summer months from 1909 through 1919 at the control station in the western yellow pine type. These records, as well as those shown in Figure 26, are from a free water surface.

TABLE 20.—*Monthly evaporation from free water surface at control station (Fort Valley, Ariz.), western yellow pine type, 1909–1919*

Year	May	June	July	August	September	October	Total, May–October
1909	----------	----------	4.28	3.79	3.99	3.28	----------
1910	6.08	8.71	5.92	5.56	4.89	4.46	35.62
1911	6.18	6.75	7.40	4.53	3.04	2.48	30.38
1912	5.20	6.46	4.61	5.16	5.06	3.92	30.41
1913	6.10	6.95	5.16	4.74	2.87	3.16	28.98
1914	5.14	5.22	3.56	4.16	4.59	1.44	24.11
1915	[1] 5.52	7.85	6.22	5.47	4.44	----------	----------
1916	7.50	8.10	5.24	4.17	2.89	1.94	29.84
1917	[1] 3.41	7.52	4.43	4.00	5.10	2.60	27.06
1918	5.40	4.86	3.54	3.46	3.35	2.43	23.04
1919	4.34	6.00	2.79	3.43	3.58	1.51	21.65
Average	5.49	6.84	4.83	4.41	3.98	2.72	27.90

[1] Interpolated in part.

Investigators sometimes make use of a moisture ratio, expressing the relation between precipitation and evaporation. (Table 19, last column.) Theoretically, this ratio should afford a very good index of moisture conditions, but it can be applied only where evaporation and precipitation have been measured contemporaneously. In this study winter records of evaporation were not obtained in the higher altitudes because of the complications introduced by freezing and heavy snowfall. In order to have a comparable series it has therefore been necessary to limit the period to four months, June to September.

SOIL MOISTURE

The quantity of moisture in the soil, accurately determined, constitutes the best single expression of moisture conditions. It is the net proceeds of precipitation minus run-off and evaporation. The effectiveness of moisture in promoting plant growth depends upon what proportion escapes direct evaporation from the surface soil, upon the fertility of the soil, and upon the efficiency of the plant mechanism in storing or making use of the water it absorbs. Some plants are capable of more growth than others with a given amount of water; most plants make better use of soil moisture on fertile soil; in all cases atmospheric conditions determine the efficiency of the plants' use of water by their influence on transpiration. High temperature, high wind movement, and low atmospheric humidity favor rapid dissipation of soil moisture. High temperature, within certain limits varying with different plants, also favors rapid growth; but high wind movement and low humidity tend to retard growth and decrease the effectiveness of soil moisture in the plant not habituated to these conditions.

One of the chief obstacles in the way of employing determinations of soil moisture on a broad scale is the mechanical difficulty of obtaining representative soil samples and determining their water content. After this laborious and time-consuming task has been accomplished, there remains the complication introduced by varying wilting coefficients [14] which must be known for each soil in order to determine what proportion of the total moisture supply is available for the use of plants. The calculated moisture percentages often fail to express the true condition, either because individual soil samples are not truly typical of the site they represent or because the wilting coefficient was not based upon a typical sample.

Another consideration in comparing soil-moisture data from different sites is the density of the vegetation, since growing plants draw moisture from the soil in quantities which may far exceed the loss by direct evaporation. In the forest the reduction of soil moisture is brought about not only by the small plants directly on the spot where the sample is taken but also by the roots of trees that stand as much as 100 feet distant. This effect would be removed if the vegetation were destroyed and the invading roots cut. If the main purpose were to measure the total potential moisture supply, removing the vegetation would be the proper procedure; but this study is concerned more with the actual conditions under which the forests are growing. Therefore, samples were taken in situations which were considered to represent average root activity.

The foregoing remarks may explain some of the apparent discrepancies in the data here presented. Although these circumstances tend to detract from their value, soil moisture data are still to be rated as our best means of studying moisture conditions in relation to

[14] Wilting coefficient indicates the point to which moisture in the soil must be reduced in order to cause permanent wilting in plants. The amount above this point is termed "available moisture" or "growth water" and that below is termed "nonavailable." The last term is not strictly accurate because plants may continue to draw water from the soil after permanent wilting has taken place, although the amount is too small to sustain life.

the growth of plants. The data here presented are confined to the San Francisco Mountains; it may be assumed, however, that they are indicative of moisture conditions in other regions under similar conditions of rainfall, soil, and cover.

COMPARISON BETWEEN FOREST TYPES

Figures 28 and 29 bring out the soil-moisture relations between the several forest types of the San Francisco Mountains, as recorded in 1918 and 1919. It should be noted that the precipitation graphs trace the readings of the month just preceding. In neither of these years was precipitation typical of the region. In 1918 the total was about normal, but the summer rains began in the middle of June, whereas usually they begin anywhere from the first to the middle of July. In 1919, heavy rainfall extending over nearly two weeks in the last half of May forestalled the usual June drought. In both these years the distribution during April, May, and June was more typical of New Mexico and Colorado than of Arizona. Soil samples were also taken during 1920, but only in the western yellow pine type. The rainfall during April, May, and June of this year proved to be fairly typical, but the summer rains were below normal.

Soil moisture determinations at a depth of 1 or 2 inches (fig. 29) show the usual sharp fluctuations characteristic of surface conditions. In most years the available moisture would have been a minus quantity, or below wilting coefficient, throughout the month of June in the western yellow pine type. As it was, the zero line was reached only toward the end of the month in the western yellow pine and not at all in the Douglas fir and Engelmann spruce. The high records in July and August are significant in relation to germination, which usually takes place during these months. In only one instance has western yellow pine been known to germinate in May or June. This was in 1919, when the heavy rainfall in May promoted abundant germination and enabled a good proportion of the seedlings to live through June until the arrival of the July rains. Even in that year, however, most of the western yellow pine seeds lay dormant until daily showers in July provided ideal conditions for growth. In the Douglas fir and Engelmann spruce types seedlings sometimes appear in June but most commonly do not come up until July.

Soil samples taken at depths of 6, 12, and 24 inches represent the strata in which nearly all the roots occur. Western yellow pine and Douglas fir send a few roots down to 4 feet, or even deeper, depending upon the permeability of the soil, but the great mass of feeders lies within 2 feet of the surface. The roots of Engelmann spruce and its associates go very little below 1 foot. The shallow rooting of western yellow pine in the vicinity of the San Francisco Mountains, as compared with its habit in some other localities, is believed to be due to heavy subsoil. In one place where the roots stopped on reaching hardpan at a depth of about 2 feet, a crevice extending down to a depth of 4 feet and filled with sand and gravel contained a dense mat of roots. The shallow rooting of Engelmann spruce and its associates in this region is not due to impermeable soil, for the soil is exceedingly porous. It may be inherent in these species or be due to the fact that the surface foot of soil is usually well supplied with moisture. Soil temperature may also be a factor.

According to Figures 28 and 29, no serious drought occurred below the surface layer in either year, except in the piñon-juniper type in 1918. In 1920, however, the available moisture at the 6-inch

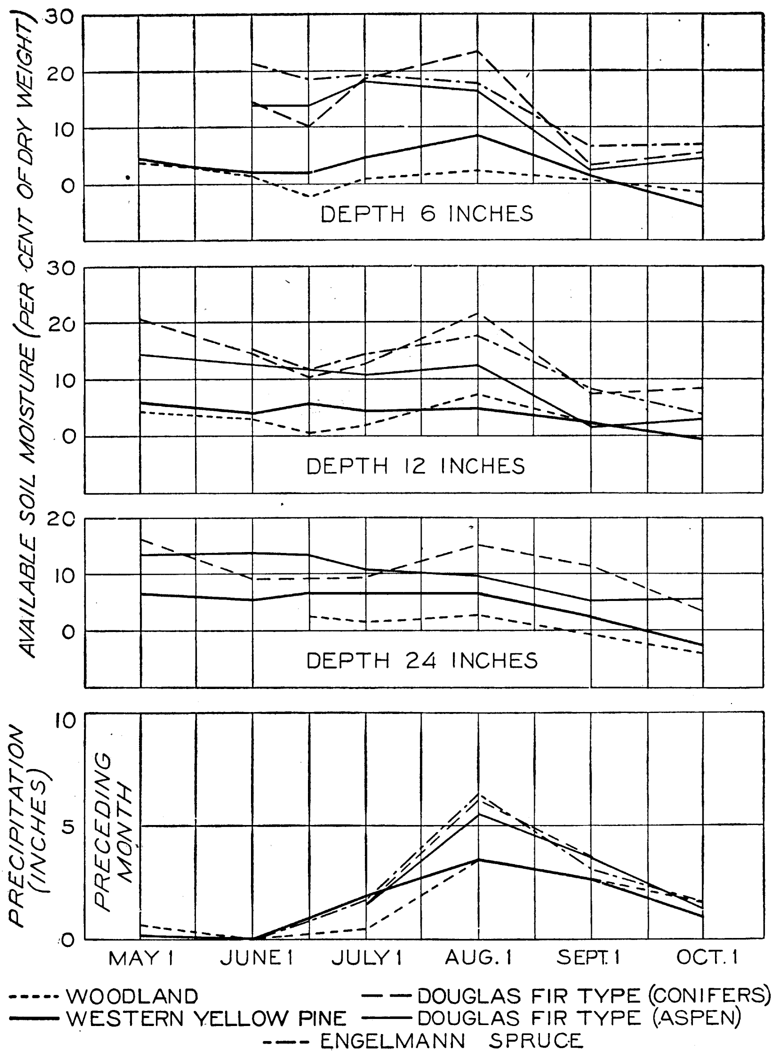

FIGURE 28.—Available soil moisture in different forest types, San Francisco Mountains, 1918

depth fell to the zero line in the western yellow pine type in June and again in September. Previous records in the western yellow pine have shown that for depths of 12 inches or less, complete or nearly complete exhaustion of growth water may usually be expected in the latter part of June. All information at hand indicates that

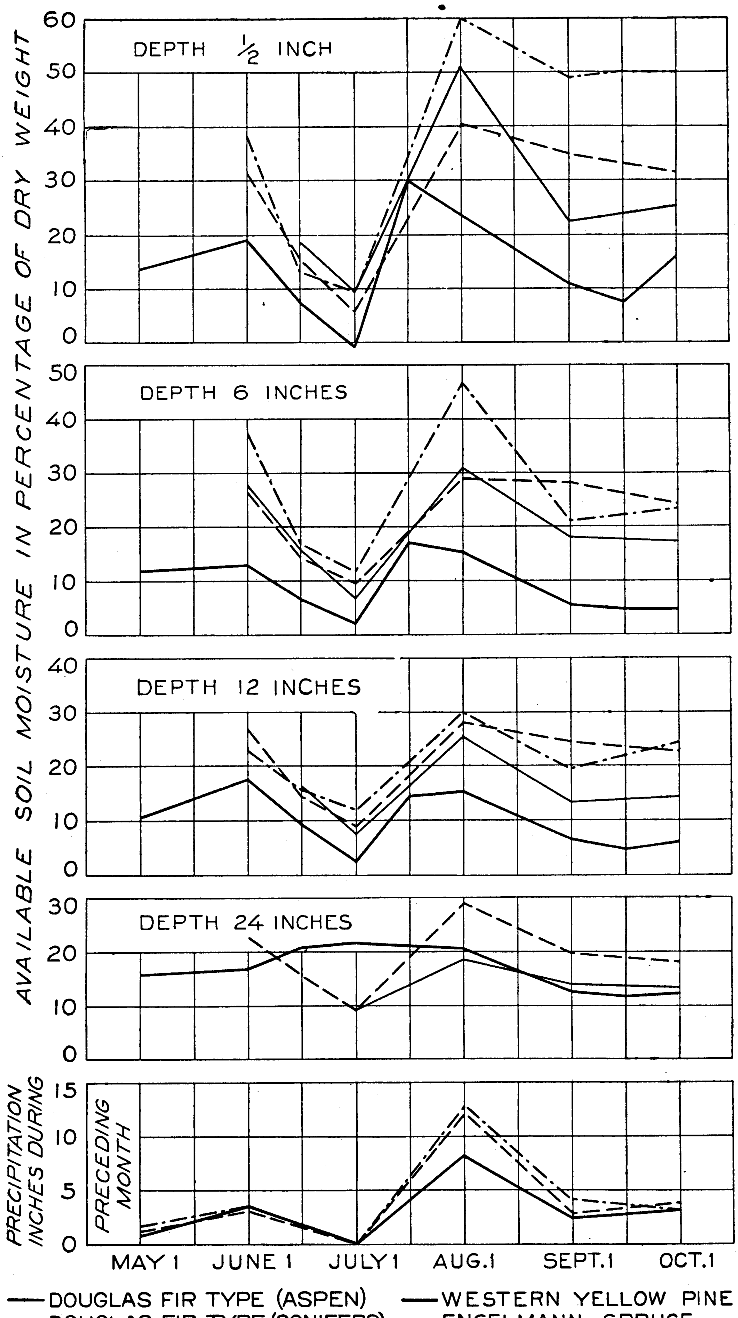

FIGURE 29.—Available soil moisture in different forest types, San Francisco Mountains, 1919

far more extended depletion is the rule in the piñon-juniper type. In the Douglas fir and Engelmann spruce types, droughts during the main growing season must be exceedingly rare. In the spruce type, the greatest depression is likely to come late in the summer when growth is at its height, as in 1918. In 1919, a depression was noticeable in the latter part of August but, because of the abnormally heavy rainfall in this type, amounting to 7.09 inches more for July and August than in the preceding year, was less pronounced than in 1918. When the tremendous water consumption of a dense stand of growing spruce or fir is considered, it is conceivable that the moisture supply may be taxed even with a monthly rainfall of nearly 5 inches. A similar late-summer depression may occur in western yellow pine stands in years of average or deficient rainfall.

At a depth of 24 or more inches moisture sufficient to sustain plant growth is usually to be found through the main growing season in all forest types, except woodland. This supply of moisture is attributed to the heavy winter precipitation in the higher types. On several occasions excavations in the western yellow pine type at the Fort Valley station have shown the soil to be well saturated in the spring of the year to a depth of 6 feet. In the woodland zone, however, nearly dry soil has been found in May at a depth of 2 feet. Above the western yellow pine type snow persists so late that the dry period in the late spring and early summer usually experienced in lower altitudes is scarcely perceptible. This is especially true of the Engelmann spruce type, where the snow lies well into June.

VARIATIONS WITHIN FOREST TYPES

Moisture determinations have been made in treeless openings of the western yellow pine type and woodland, in aspen thickets of the Douglas fir type, and in openings in spruce stands, with a view to ascertaining whether soil moisture is a factor in creating these openings.

Woodland Parks

Samples representing the typical soil of piñon-juniper woods were taken on a rocky upland situation, and those representing the park were taken in a sparsely wooded valley about 50 yards distant. Limestone is the prevailing rock in this locality. The upland soil is generally so stony that holes a foot deep can be dug only with great difficulty. The vegetation in addition to trees consists of a sparse growth of grama grass, sage, and various other shrubs. In the valleys the soil is practically free of stones. Grama grass covers about one-half of the ground surface. Samples at 6-inch and 12-inch depths in 1918 indicated a consistently lower available moisture content in the valley during the driest periods. A few samples taken in 1918 showed the same relation.

Western Yellow Pine Parks

In the western yellow pine type comparisons were made between the forest, the edge of the forest, and a large park or valley devoid of trees. In the forest, the samples were taken on a level site within an area reached by the roots of large trees. The soil here is stony clay loam derived from basalt and typical of the western yellow pine forest in this locality. The transition between forest and park is marked at this point by a rather abrupt slope to the southeast, descending about 25 feet from the forest to the floor of the valley. Samples were taken midway of the slope, where the soil is very gravelly but comparatively free from large stones. Roots from neighboring trees and saplings reach the area, and seedlings from 7 to 10 years old are abundant. The valley soil is free from stones but contains a moderate proportion of sand and gravel. The sticky clay subsoil characteristic of the forest does not occur here. Over considerable portions of the valley a hardpan of cemented gravel

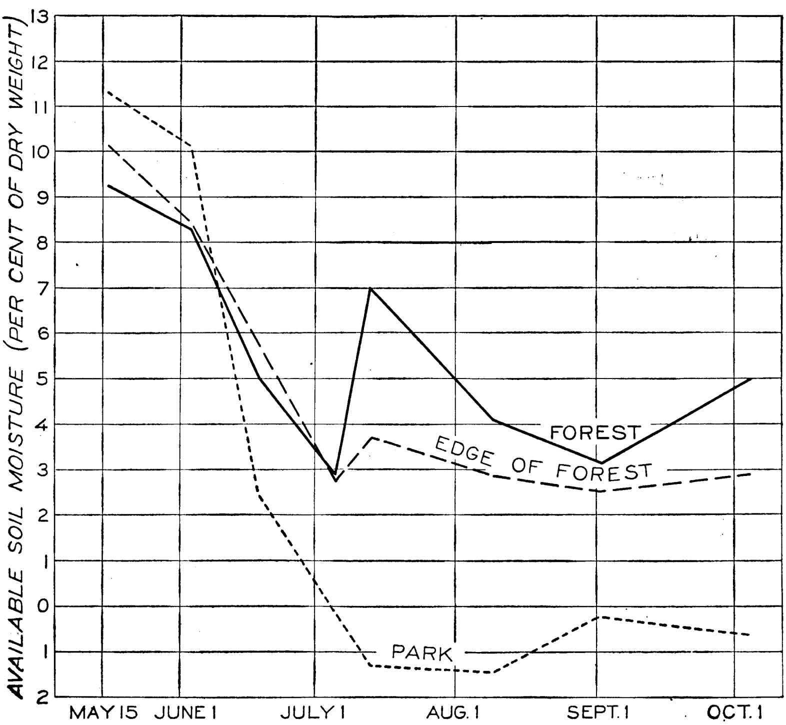

FIGURE 30.—Available soil moisture in forest and park, western yellow pine type, 1920, depth 12 inches

and cinders is found 12 to 18 inches below the surface, but this layer was not encountered down to 2 feet at the point where the samples were taken.

In comparing the wilting coefficients on the three sites (Table 21) it will be seen that the highest values are those of the forest and the lowest those of the slope, values in the park being intermediate. The topography would lead one to expect the heaviest soil in the park, but extremely heavy soils are found only in the depressions.

The park area where the samples were taken bears a grama-grass sod of about 0.4 density and scattered plants of tall larkspur and a few other herbs. This vegetation remains relatively inactive until the arrival of the summer rains in July, when, if the rains are abundant, it becomes luxuriant.

In 1919, a year of abnormally heavy rainfall, available moisture was highest in the forest but only slightly lower in the park. The slope between forest and park has much the lowest values during periods of abundant rainfall, but when a drought of several weeks occurs the value here tends to hold up better than in other situations. This relationship was strongly brought out in 1920, which was a year of subnormal rainfall through the growing season. (Fig. 30.) The slope had the highest values in June and early July, particularly at a depth of 6 inches. Neither the slope nor the forest soil approached dangerously near the wilting point, but the park soil was below the wilting point during a large portion of the summer. This study points toward unfavorable moisture conditions as an important and perhaps the dominant factor in explaining the absence of a western yellow pine forest in the parks.

Table 21.—*Available soil moisture in percentage of dry weight at different depths by forest types, San Francisco Mountains, on different dates, 1918–1920*

1918 RECORDS

Depth and forest type	Station No.	Wilting coefficient	May 1	June 1	June 15	July 1	Aug. 1	Sept. 1	Oct 1
6 inches:									
Piñon-juniper—			*P. ct.*	*P. ct.*	*P. ct.*	*P. ct.*	*P. ct.*	*P. ct.*	*P. ct.*
Stony mesa	4A	8.1	3.9	1.9	−2.0	1.1	2.6	0.7	−1.4
Valley	4B	10.7	.6	1.6	−2.0	−1.3	4.4	−3.5	−3.6
Western yellow pine	1A	12.4	4.3	1.5	1.8	4.7	8.3	1.2	−4.1
Douglas fir—									
Conifers	8A	8.0	------	14.4	9.8	18.5	23.7	3.3	5.5
Aspen	8B	6.5	------	14.9	13.8	18.0	16.5	2.1	4.4
Limber pine-bristlecone pine—									
Open southwest slope	9	6.5	------	4.4	2.4	------	------	------	5.6
Engelmann spruce—									
Forest (northwest slope)	10A	5.7	Snow	21.1	18.3	19.4	17.8	6.6	7.0
Opening (ridge)	10B	7.8	------	24.8	12.1	23.6	18.7	3.7	12.0
12 inches:									
Piñon-juniper—									
Stony mesa	4A	8.4	4.2	2.9	.6	1.8	7.1	2.1	−.4
Valley	4B	12.3	2.3	1.4	−2.0	.6	4.4	------	−6.1
Western yellow pine	1A	12.8	5.9	3.8	5.7	4.4	5.1	2.1	−.5
Douglas fir—									
Conifers	8A	7.7	20.4	14.7	10.2	12.5	21.8	7.6	8.6
Aspen	8B	7.1	14.4	13.0	11.3	10.8	12.7	1.7	3.2
Limber pine-bristlecone pine—									
Open southwest slope	9	7.0	6.2	3.3	5.9	7.8	12.2	1.3	7.2
Engelmann spruce—									
Forest (northwest slope)	10A	7.5	Snow	15.0	11.6	14.2	17.8	8.1	3.8
Opening (ridge)	10B	7.7	26.5	21.6	22.8	11.7	19.8	14.2	7.7
24 inches:									
Piñon-juniper—									
Valley	4B	10.6	------	------	2.2	1.5	2.9	−.8	−4.0
Western yellow pine	1A	15.1	6.8	5.4	6.5	6.3	6.5	2.6	−2.5
Douglas fir—									
Conifers	8A	6.5	16.6	9.3	9.8	9.3	14.9	11.2	3.6
Aspen	8B	5.5	13.7	13.9	13.8	10.5	9.7	5.2	5.6

1919 RECORDS

Depth and forest type	Station No.	Wilting coefficient	May 1	June 1	June 15	July 1	July 15	Aug. 1	Sept. 1	Sept. 15	Oct. 1
Surface one-half inch underneath litter:											
Western yellow pine—		P. ct.	P. ct.	P. ct.	P. ct.	P. ct.	P. ct.	P. ct.	P. ct.	P. ct.	P. ct.
Forest		8.3	14.3	19.2	7.4	−0.8	31.2	24.3	10.4	7.9	14.7
Edge of forest	1A	7.7	------	12.7	------	------	14.3	13.4	6.0	------	------
Park		8.0	------	19.0	------	------	22.8	29.0	26.8	------	------
Douglas fir—											
Conifers	8A	7.4	------	31.6	15.6	6.0	------	41.0	35.1	------	32.1
Aspen	8B	8.7	------	------	18.8	9.0	------	51.0	22.4	------	26.2
Engelmann spruce—											
Forest (northwest slope)		8.9	------	39.4	13.9	8.9	------	60.6	49.4	------	50.6
Opening (northwest slope)	10A	6.6	------	32.1	8.3	13.5	------	61.4	21.7	------	34.8
Forest (ridge)		12.3	------	------	14.3	7.2	------	56.4	54.4	------	36.8
Opening (ridge)	10B	7.2	------	53.9	21.8	21.0	------	34.9	41.5	------	38.8
6 inches:											
Western yellow pine—											
Forest		13.5	11.9	12.8	6.5	2.2	17.0	15.3	5.4	4.4	4.4
Edge of forest	1A	9.0	11.6	12.0	5.3	3.2	16.1	15.7	------	------	------
Park		10.8	12.0	15.8	6.1	−1.0	20.0	19.3	6.4	------	------
Douglas fir—											
Conifers	8A	8.0	------	26.6	14.4	9.4	------	29.0	28.2	------	24.0
Aspen	8B	6.5	------	28.0	15.9	7.0	------	30.9	18.2	------	17.2
Engelmann spruce—											
Forest (northwest slope)		5.7	------	38.3	16.8	11.6	------	47.5	20.9	------	23.3
Opening (northwest slope)	10A	7.2	------	19.3	12.0	9.1	------	36.4	28.8	------	45.2
Forest (ridge)		8.7	------	------	20.6	10.8	------	41.5	29.5	------	31.1
Opening (ridge)	10B	7.8	------	33.5	21.9	20.3	------	36.4	30.6	------	28.8
12 inches:											
Western yellow pine—											
Forest		16.0	10.8	17.6	9.0	2.2	14.5	15.2	6.1	4.9	5.9
Edge of forest	1A	8.8	------	11.8	7.4	4.5	14.1	14.0	5.5	------	------
Park		11.4	11.1	13.0	8.6	1.8	16.1	16.0	9.1	------	------
Douglas fir—											
Conifers	8A	7.7	------	27.1	14.9	8.7	------	28.2	24.6	------	22.7
Aspen	8B	7.1	------	------	16.3	7.8	------	25.6	13.7	------	14.4
Engelmann spruce—											
Forest (northwest slope)		7.5	------	23.0	15.5	11.8	------	30.1	19.7	------	23.9
Opening (northwest slope)	10A	7.4	------	29.4	12.2	10.5	------	27.5	22.2	------	19.2
Forest (ridge)		7.8	------	------	17.1	14.1	------	25.2	24.7	------	23.5
Opening (ridge)	10B	7.7	------	28.2	21.3	20.3	------	25.1	31.7	------	28.9
24 inches:											
Western yellow pine—											
Forest		16.6	15.3	16.2	20.4	21.3	20.7	20.3	12.4	11.4	12.0
Edge of forest	1A	8.8	------	13.0	7.2	9.6	14.2	14.9	10.3	------	------
Park		10.2	4.9	10.8	11.0	9.9	17.1	17.4	13.3	------	------
Douglas fir—											
Conifers	8A	6.5	------	23.0	15.0	9.3	------	29.2	19.4	------	18.4
Aspen	8B	5.5	------	------	14.9	9.3	------	18.8	13.4	------	13.1
Engelmann spruce—											
Forest (northwest slope)		6.2	------	20.0	------	------	------	10.6	------	------	------
Opening (northwest slope)	10A	4.4	------	22.1	------	------	------	20.8	------	------	------
Forest (ridge)		8.3	------	------	------	------	------	21.2	------	------	------
Opening (ridge)	10B	9.3	------	22.1	------	------	------	23.5	------	------	------

1920 RECORDS

Depth and forest type	Station No.	Wilting coefficient	May 17	June 4	June 19	July 6	July 14	Aug. 9	Sept. 3	Oct. 6
6 inches:										
Western yellow pine—		P. ct.	P. ct.	P. ct.	P. ct.	P. ct.	P. ct.	P. ct.	P. ct.	P. ct.
Forest		13.1	7.0	4.5	1.8	------	2.9	6.4	0.1	0.6
Edge of forest	1A	9.0	8.8	7.9	3.1	1.2	1.8	4.8	1.8	2.2
Park		10.8	10.8	6.9	−.4	−.7	−3.2	.6	−.5	−.8
12 inches:										
Western yellow pine—										
Forest		15.4	9.2	8.3	5.0	2.9	7.0	4.1	3.1	5.0
Edge of forest	1A	8.8	10.2	8.4	5.4	2.8	3.8	2.9	2.6	3.0
Park		11.4	11.3	10.1	2.5	.2	−1.2	−1.4	−.2	−.6

Western yellow pine seedlings from 7 to 12 years old are scattered through a large portion of this park. Whether they will persist to tree size remains to be seen, since where hardpan occurs within 2 feet of the surface they will not be able to reach the lower soil strata upon which they ordinarily depend to tide them over dry periods. Plantations in the park have made a promising start but have failed after two or three years, due mainly to winterkilling.

Aspen Areas

The aspen stands of the Douglas fir zone and the lower portion of the Engelmann spruce zone present a problem somewhat different from that of the parks. Here is found direct evidence of the former existence of a conifer forest which was destroyed by fire. In many places where seed trees remain the conifers are coming back satisfactorily. Elsewhere, however, the conifers are returning, if at all, so slowly as to raise a doubt whether all the aspen areas are truly suited to a conifer forest. Climate is clearly not a controlling factor. The reactions to differences in topography are not consistent. Though aspen attains greatest size in the depressions, it is abundant and often grows to good size on steep slopes.

In the present study soil samples were taken in a Douglas fir stand on a northwest slope at the Douglas fir weather station and also in a stand of aspen on a nearly level bench about 50 yards distant. Evaporation and soil temperature are practically the same at the two stations. The only conspicuous differences in the soils of the two sites are a greater abundance of bowlders in the Douglas fir forest and a darker color in the surface layers of the aspen soil. The wilting coefficients at depths of 6, 12, and 24 inches are slightly lower in the aspen, contrary to what one would expect if the soil were unfavorable to conifers. A few conifers are scattered over the area, though the number is not commensurate with the quantity of seed available. Experimental plantations of Douglas fir and blue spruce on the aspen site have given encouraging results at the end of seven years. Herbaceous cover consisting of such plants as vetch, geranium, columbine, and bromegrass grows luxuriantly in the aspen but rather sparingly among the conifers.

Soil samples taken in 1918 and 1919 (Table 21) indicated a lower percentage of available moisture in the aspen stand than in the conifer; yet there is no suggestion of drought. The differences noted may be attributed rather to greater water consumption of the aspen and the rich herbaceous growth beneath it than to inherent differences in characteristics of the soil. The conclusion, therefore, is that, as far as soil moisture and other soil conditions are concerned, the aspen-covered area is practically as favorable for growth of conifers as are the areas now occupied by conifer stands. This conclusion applies to all the benches and slopes but may not apply to the lower valley lands.

Engelmann Spruce Openings

Openings from 50 to 75 feet wide, in which young growth, if present at all, is generally inadequate, are rather common in mature Engelmann spruce stands. Usually nothing about the topography or external appearance of the soil in the openings suggests conditions different from those prevailing in the forest proper. Whatever may be their origin, the fact that evidently for 50 years or more they have not been restocking gives rise to speculation, especially as in many places the remains of stumps or tree trunks tell of former productiveness and the roots of surrounding trees now extend well into the openings.

In 1918 and 1919 the moisture content at various depths in openings on a steep northwest slope and on a ridge were compared with similar measurements in adjacent spruce stands. (Table 21.) Reproduction was lacking in both places. The moisture percentages in the opening on the northwest slope tended to run somewhat below those of the timbered area, which in turn were exceeded by those of the ridge opening. In no place, however, were the moisture values dangerously low. Beds sown to Engelmann spruce and bristlecone pine in the ridge opening in 1918 and again in 1919 have produced thrifty seedlings of both species. Engelmann spruce sown in the northwest-slope opening germinated, but the seedlings died after two years. Spruce seedlings of natural origin have shared the same fate, with the exception of a few on rotten logs.[15] The probable explanation of poor survival in similar small openings on north exposures at high elevations is deficient heat, which may manifest itself through low activity of soil organisms, as found by Hesselman (*20*) in Sweden, or through retardation of plant functions dependent upon heat energy. On sunny exposures the critical factor is probably surface moisture as related to germination, because here both Engelmann spruce and bristlecone pine seedlings, once past the initial stages of establishment, grow vigorously.

SOILS

Several phases of the subject of soils have been discussed in connection with climate. Thus, soil temperature has been treated along with air temperature; soil moisture has been discussed in its relation to precipitation, evaporation, and humidity; and permeability is referred to repeatedly as a primary factor in depth and development of roots.

GEOLOGIC ORIGIN

In the region of the San Francisco Mountains, the soils are derived mainly from lavas of various forms. In addition to the San Francisco crater, there are many smaller volcanic cones, all of which have contributed material in the form of lava flows, fragmental blocks, or cinders (*37*). On San Francisco Peak, which appears to be typical of the higher portion of the San Francisco Plateau, the rocks above 8,000 feet are largely of the acidic or subbasic volcanic type consisting of andesite, latite, dacite, and rhyolite. The last,

[15] Survival on rotten logs has also been pointed out by Lowdermilk (*27*) in the Northwest. He attributes this to favorable surface moisture. In this region, however, moisture is not the solution, since here the soil is almost continually moist on as well as beneath the surface, and, as has been pointed out, the seedlings survive for two or three years. It is more likely that the impetus given by the logs is of a chemical nature. Whatever this benefit may be, the unthriftiness of the seedlings indicates that it is inadequate.

which is the most highly acidic, occupies only small areas. In contrast to the acidic rocks are the basic basaltic rocks at lower elevations. Massive basalts underlie the surface 10 to 15 miles or more from the foot of the mountain, overlying the earlier sedimentary formations. Of the sedimentary formations, the most extensive is the Kaibab (Pennsylvanian), which consists mainly of a grayish, more or less arenaceous limestone containing magnesium in places and nodules of chert commonly. Thin layers of sandstone occur with the limestone in places, often almost completely distintegrated but traceable in the form of sandy material. Underneath the Kaibab formation lies the grayish or yellowish Coconino sandstone. This appears only in canyons or on the rim of the plateau and therefore is unimportant in relation to the forest soils of this region. The Moencopi formation consists of reddish sandstone or reddish, sandy shale. It appears on the surface only over small areas.

In addition to volcanic and sedimentary formations similar to those here mentioned granite occurs over a large part of the forest regions of Arizona and New Mexico. No attempt is made here to describe the geologic formations of the entire region, partly because the information is not available and partly because such a description is not considered necessary to this investigation. Although the geologic source of a soil may be of great importance, other factors, such as topography and climate, are of equal or greater importance. For this region, a map showing the geologic origin of the soils would have no great significance in a study of forest types unless correlated with an equally intensive study of other factors. Students of the soil problem are coming more and more to the conclusion that a classification of soils with reference to growth possibilities must be based on the actual condition and composition of the soil itself. This includes both chemical and physical conditions—the thickness of the soil as a whole and of its separate horizons, its fertility, moisture relationships, penetrability, reaction, and the amount and stage of humification of organic matter—all of which are determined primarily by climate, with geology as a modifying factor.

CHEMICAL COMPOSITION

The chemical composition of forest soils is important but has been studied in only a fragmentary manner, owing to its complexity and the difficulty of performing adequate analyses in the course of ordinary forest investigations. A large number of samples would be required to represent a single soil type in one locality. Moreover, even if adequate analyses were available, the knowledge to interpret correctly their significance in relation to the growth of various forest trees is still lacking. Chemistry of forest soils offers an important field for further experimental research.

As has been pointed out, chemical composition is but one of the several factors involved in the productive capacity of soils. Not only are other factors important, but they may react upon the chemical condition. Temperature and precipitation in a region of such great extremes as the Southwest usually determine both the kind and the total amount of vegetation, and this, in turn, determines the amount of organic matter, which in addition to influencing texture is the main source of nitrogen.

The ability of soil organisms to live and function is greatly influenced by temperature and moisture. In very cold climates, especially if the soil is poorly aerated, organic matter is not completely converted into available nitrates because conditions are not suitable for proper bacterial action. In hot, dry climates organic matter near the surface of the soil may be lost by chemical oxidation or slow burning. Undoubtedly this is the fate of much of the vegetable matter deposited on the ground surface in zones below the Douglas fir type.

Precipitation directly affects the soluble salts in the soil or in the parent rocks by leaching them out of the surface layers and either carrying them away or depositing them in lower soil horizons. In humid climates there is often a deficiency of soluble salts, due to excessive leaching. In semiarid climates these salts are usually abundant, but they may be deposited in excess in layers a few inches below the surface. In undrained flats or basins receiving the drainage from semiarid lands, salts or alkali often accumulates to such an extent as to be harmful to vegetation.

Chemical analyses by the Bureau of Chemistry and Soils of samples in the various forest types from the western yellow pine up to the alpine type are given in Table 22. Perhaps the most significant difference is in the nitrogen content, which increases irregularly with rising altitudes up to timber line. The types above western yellow pine also show a rise in calcium oxide.[16] The report on these analyses by the Bureau of Chemistry and Soils states that all the samples are approximately neutral in reaction and contain no excess of soluble salts. Local tests of alkalinity and acidity, by the Wherry method, of another set of samples including grassland and piñon-juniper soils are given in Table 23. These show slight alkalinity in the grassland and piñon-juniper types, the latter including both limestone and basalt; practically a neutral reaction in the western yellow pine type on both basalt and cinders; and slight acidity in the Douglas fir, Engelmann spruce, and alpine types. In view of the fact that both the basaltic and the limestone soils in the western yellow pine type are neutral, the alkalinity of the soils derived from these rocks in the woodlands and in the grassland should not be attributed to excessive alkaline characteristics of the rocks in the lower altitudes but rather to low precipitation which may cause an accumulation of soluble salts near the surface instead of washing them away or carrying them into the deeper strata. The slight acidity of the soils above the western yellow pine type might be attributed to the fact that they are derived from rocks which normally have an acid reaction; but more likely it is due to the presence of quantities of organic matter not adequately decomposed because of low temperatures in the high altitudes.

[16] According to Cajander (8), investigations in Finland have shown a strong correlation between site quality and the presence of calcium oxide and nitrates. In both Scotch pine and birch stands the highest increment is found on soils rich in these compounds. Potassium oxide shows a low correlation with increment, and phosphoric acid none at all.

TABLE 22.—*Chemical analyses*[1] *of soils in different forest types of the San Francisco mountain region*

Forest type and soil origin	Depth	Lime (CaO)	Potash (K_2O)	Phosphoric acid (P_2O_5)	Nitrogen (N)
	Inches	*Per cent*	*Per cent*	*Per cent*	*Per cent*
Western yellow pine bark (basalt)	0–2	2.76	2.05	0.21	0.11
Do	12	1.98	2.01	.24	.11
Western yellow pine forest (basalt)	0–2	2.37	2.26	.20	.16
Do	12	2.05	2.23	.18	.12
Western yellow pine forest (Kaibab limestone)	0–2	2.39	1.93	.13	.11
Do	12	.87	.96	.12	.04
Douglas fir (acidic volcanic)	0–2	4.77	2.09	.12	.33
Do	12	4.43	1.79	.16	.20
Engelmann spruce (acidic volcanic)	0–2	3.81	3.16	.15	.26
Do	12	4.34	1.89	.13	.09
Timber line (acidic volcanic)	0–2	5.65	2.02	.30	.32
Do	12	4.16	2.01	.25	.18

[1] Analyses by U. S. Bureau of Chemistry and Soils.

TABLE 23.—*Acidity and alkalinity of soils at a depth of 6 inches in different vegetational zones of the San Francisco Mountain region*

Forest type and soil origin	Location	Altitude	pH[1]
		Feet	
Grassland (Kaibab limestone)	East of Canyon Padre	5,000	8.2
Piñon-juniper (Kaibab limestone)	Near Walnut Canyon, ridge	6,500	8.0
Do	Near Walnut Canyon, valley	6,500	8.0
Western yellow pine (basalt)	Sample plot S-3-A	7,300	7.0
Do	Fort Valley	7,300	7.0
Western yellow pine (cinders)	East of cliffs	7,000	7.0
Douglas fir (acidic volcanic)	San Francisco Mountains	8,700	7.0
Douglas fir-aspen (acidic volcanic)	do	8,700	6.8
Engelmann spruce (acidic volcanic)	do	10,500	6.5
Timber line (acidic volcanic)	do	11,500	6.5

[1] Determinations by the Wherry method (*47*). Values above pH 7 indicate alkalinity; those below, acidity.

PHYSICAL CHARACTERISTICS

Investigations in the western yellow pine zone have shown that within soil areas of similar origin growth is usually best in the more sandy or gravelly soils. (Fig. 31.) This relation is so general in the Southwest that texture appears to be more important than chemical composition, particularly in the growth of seedlings. (Fig. 32.) Also in clay soils reproduction is always better where there is a mixture of rocks. Similar observations made in the Douglas fir zone again point to permeability as the dominant factor. It is a matter of common observation that western yellow pine roots penetrate most deeply in the sandy or gravelly soils (fig. 33, A and B), probably because these soils are also most permeable to moisture and air. Penetration is also good among rocks, provided they do not offer excessive mechanical resistance.

Topography, geologic origin, and climate all have an important bearing upon physical composition of soils. Naturally the finest soils are found in the valleys, although there may be sandy or

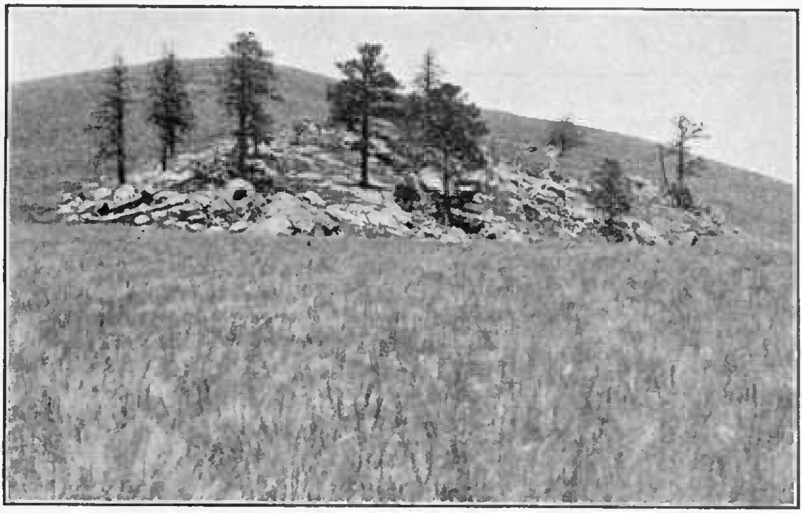

FIGURE 31.—Western yellow pine on a rocky eminence in a park within the western yellow pine type. The surrounding grass-covered area has a clay loam or clay soil, usually unfavorable to pine reproduction unless mixed with a large proportion of stones. (Photo by J. O. Veatch)

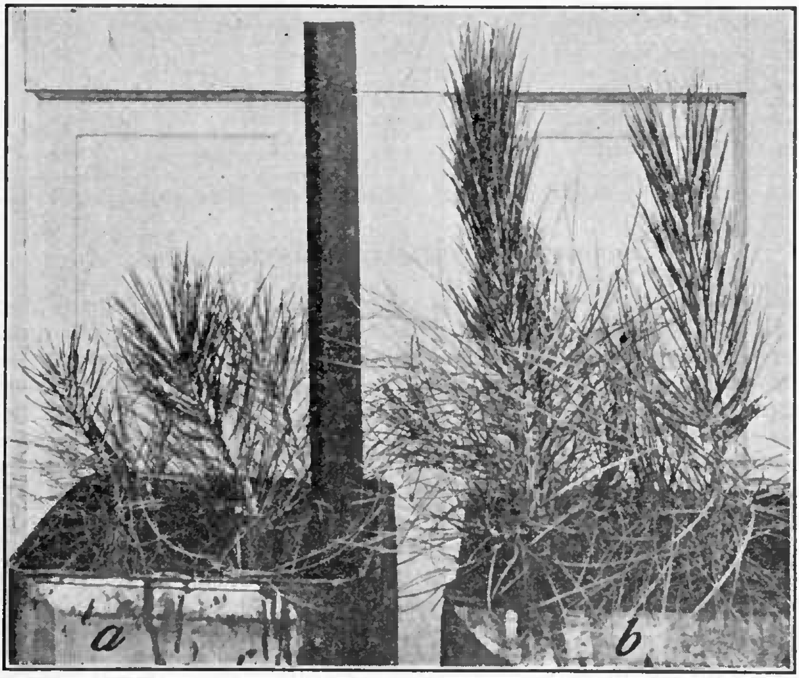

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FIGURE 32.—Western yellow pine seedlings of the same age in two kinds of soil: *a*, Clay subsoil from western yellow pine forest; *b*, surface soil mixed with 50 per cent sand

gravelly deposits in such situations. Slopes are more likely to be made up of coarse material, especially if bare enough to permit surface erosion. A good illustration of the effect of geological formation is seen in comparing soils derived from basalt on the Colorado Plateau with those from the so-called acidic rocks where they occur under similar conditions of climate and topography. The acidic rocks are more crystalline and when disintegrated yield a greater proportion of sand and less clay than does the basalt. The basaltic soils are usually very heavy, and but for the presence of

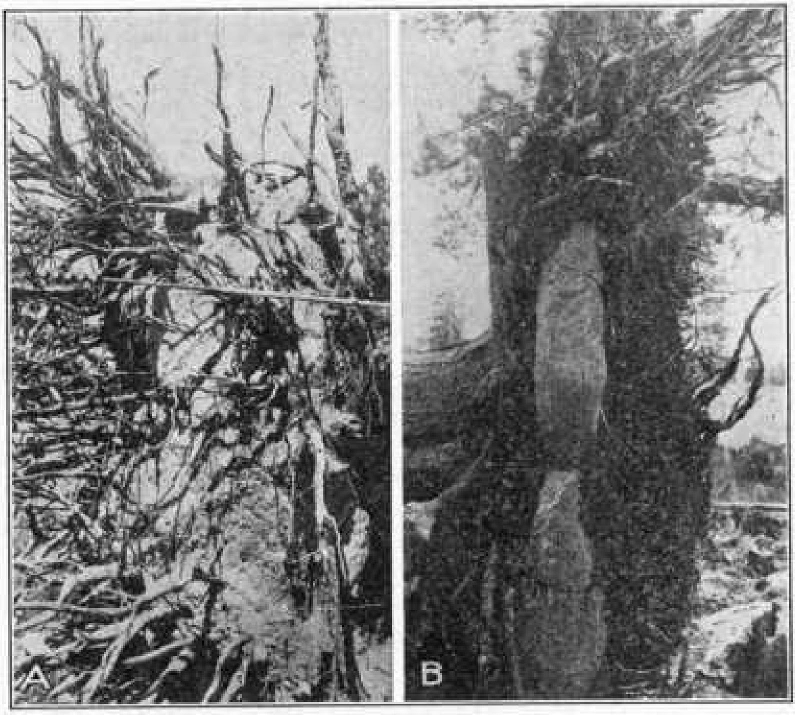

FIGURE 33.—Root systems of western yellow pine in different soils: A, On deep gravelly soil. Here there is no well-defined taproot but a large number of small ones which go straight down. The lateral system near the surface is also strong. The auger shown near the center of the picture is 40 inches long. B, Shallow root system typical on the more compact soils

organic matter, rocks, and gravel beyond the largest size considered in the mechanical analyses here presented, would be somewhat impermeable, especially after being thoroughly leached. Table 24 shows this relation fairly consistently. The limestone and sandstone vary considerably but usually yield a fairly permeable soil. The subsoil in the Kaibab limestone formations is commonly a heavy clay. Perhaps the most porous soil and one of the most productive under favorable conditions of climate and topography is the disintegrated granite. On steep slopes, however, unless a good vegetative cover is maintained, it tends to erode badly, with consequent loss of fertility.

TABLE 24.—*Physical characteristics of soils in the San Francisco Mountain region*

Laboratory sample No.	Forest type and site, with soil origin	Vegetation	Depth	Moisture equivalent [1]	Wilting coefficient [1]	Water-holding capacity	Mechanical analysis [2]						
							Fine gravel	Coarse sand	Medium sand	Fine sand	Very fine sand	Silt	Clay
			Inches	Per cent	Per cent	Per cent	Per cent	Per cent	Per cent	Per cent	Per cent	Per cent	Per cent
	Western yellow pine:												
47	Valley (Kaibab limestone, few stones).	Forest logged, tall grass	0–2	20.61	11.20	51.05	4.0	2.3	0.5	11.4	36.6	36.5	8.6
48	do	do	12	9.30	5.05	40.45	2.2	3.1	.8	24.8	49.0	14.2	5.8
49	Rocky ridge (Kaibab limestone, stony).	do	0–2	19.52	10.61	53.60	3.0	2.5	1.0	16.0	42.8	26.4	8.0
7	Level mesa (basalt, stony)	Virgin forest, grass and other herbs, close grazing.	0–2	23.70	12.88	47.85	3.1	5.4	2.4	9.5	19.4	45.9	14.2
13	do	do	12	23.40	12.72	56.80	1.3	3.6	2.6	12.1	13.0	41.6	25.9
8	do	do	12	21.39	11.62	55.80	6.0	9.3	2.4	7.1	16.6	40.2	18.3
14	do	do	24	26.04	14.15	63.00	.6	3.9	2.5	12.4	16.0	39.0	25.5
9	do	do	24	25.02	13.60	59.45	4.8	7.0	3.0	10.2	16.4	37.4	21.4
11	do	do	30	23.99	13.03	62.30	8.8	16.5	7.5	23.0	8.1	20.0	15.9
10	do	do	36	38.90	21.14	78.00	2.1	11.8	4.2	14.8	4.8	38.8	23.1
12	do	do	0–2	27.85	15.13	57.60	2.4	5.6	2.9	12.4	13.3	47.7	15.6
16	Flat (basalt, few stones)	do	0–2	25.50	13.86	48.85	1.3	4.0	2.1	9.2	18.0	50.4	14.8
17	do	do	12	24.78	13.47	62.95	1.8	5.0	2.4	11.0	14.3	40.2	25.0
18	do	do	24	26.38	14.33	64.20	2.4	5.4	2.6	10.8	10.5	43.8	24.2
4	Park (basalt, no stones)	Treeless, grama grass, close grazing.	0–2	20.49	11.13	45.63	5.4	7.6	3.2	13.0	19.0	38.2	13.6
5	do	do	12	22.70	12.34	64.65	3.0	6.8	3.3	14.2	15.0	37.2	20.5
6	do	do	21	21.85	11.87	55.13	10.6	12.0	3.6	13.3	13.4	33.2	13.9
	Douglas fir:												
31	Northwest slope (acidic volcanic, rocky).	Virgin forest, conifers	0–2	33.73	18.33	90.80	6.0	10.0	2.6	11.4	11.[illegible]	44.1	14.6
32	do	do	12	23.52	12.78	69.00	8.6	10.4	2.4	10.2	12.5	40.3	15.6
33	Bench (acidic volcanic, rocky)	Aspen and young conifers	0–2	30.95	16.82	75.55	2.6	7.3	3.2	14.4	11.3	47.3	13.9
34	do	do	12	23.99	13.03	64.30	1.6	5.8	3.4	15.1	12.6	45.8	15.4
35	Park, south slope (acidic volcanic, few rocks).	Treeless, grassy	0–2	27.65	15.03	70.80	3.0	8.2	3.3	16.2	13.4	42.2	13.6
36	do	do	12	25.53	13.88	67.90	2.1	7.4	3.8	17.3	12.2	44.6	12.6
	Limber pine-bristlecone pine:												
43	Steep southwest slope (acidic volcanic, few rocks).	Scattered pine, grassy, close grazing.	0–2	22.85	12.43	58.00	6.6	11.6	4.0	14.4	12.2	40.7	10.3
44	do	do	12	21.62	11.75	56.05	5.0	9.8	4.1	13.8	11.4	42.7	13.2
45	do	do	12	22.60	12.28	60.10	7.1	12.3	4.2	12.1	9.4	43.5	15.2

	Engelmann spruce:												
37	Northwest slope (acidic volcanic, rocky).	Dense forest	0–2	34.59	18.80	107.10	6.6	12.8	3.4	13.9	11.0	38.8	13.4
38	do	do	12	20.90	11.36	66.70	21.0	14.2	2.3	8.1	8.2	33.9	12.0
39	Ridge (acidic volcanic, rocky)	Small opening, grassy	0–2	30.60	16.63	75.80	6.2	9.1	3.4	12.1	11.2	42.8	15.0
40	do	do	12	27.30	14.84	69.15	6.8	8.4	3.1	10.5	10.0	42.4	18.7
	Timber line:												
46	Ridge (acidic volcanic)	Bushy trees, grassy	0–2	15.73	8.55	44.30	43.5	13.4	1.5	5.4	5.4	21.7	9.0
41	do	do	12	27.99	15.21	77.35	3.8	8.9	4.2	17.4	13.0	38.1	14.5
42	do	Bare	12	9.52	5.17	37.55	13.4	9.1	3.0	10.7	10.0	39.3	14.4

[1] Bureau of Plant Industry, centrifugal method. Percentages based on dry weight of soil.

[2] Bureau of Chemistry and Soils. Soil particle sizes as follows: Fine gravel, 2 to 1 mm.; coarse sand, 1 to 0.5 mm.; medium sand, 0.5 to 0.25 mm.; fine sand, 0.25 to 0.1 mm.; very fine sand, 0.1 to 0.05 mm.; silt, 0.05 to 0.005 mm.; and clay 0.005 mm. and smaller.

The capacity of soils for absorbing and holding water is termed "water-holding capacity," and the relative freeness with which they give up moisture to plants is indicated by the wilting coefficient. Soils which have the highest water-holding capacity also have the highest wilting coefficient or are able to withhold a higher percentage of water from the plant. These qualities are exhibited in the highest degree by the clay soils and in the lowest by sandy soils. Theoretically, the difference between water-holding capacity and wilting coefficient represents the net amount of water available to plant roots. But the soils having the largest capacity for available water are usually not the ones best able to sustain plant life in periods of drought.

The effects of drought are usually first apparent on clay soils, probably because of the low permeability to both water and roots. After a clay soil of good structure becomes saturated to a depth of 4 or 5 feet, the plants on it, if roots are able to penetrate to this depth, are in a position to resist drought. But if the moisture is not sufficient to saturate the lower strata or if the roots are not able to penetrate deeply the condition is different. A rainfall of 4 or 5 inches in July usually does not penetrate more than a foot in clay soil. In a sandy, gravelly, or stony soil, the same amount of moisture may penetrate 2 or 3 feet. In other words, the clay soil has a higher moisture content in the upper foot but may be dry below, and the more permeable soil has less moisture in the surface foot but stores a considerable quantity in the second and third feet. According to investigations elsewhere the water loss by evaporation from below the surface foot is very slight. Thus, if the clay soil is moist only in the surface foot all of its moisture is exposed to evaporation, whereas the more permeable soil has a supply in the second and third feet which is not affected by direct evaporation.

In the Southwest the soils of intermediate water-holding capacity and wilting coefficient usually provide the best moisture conditions. Those of low water-holding capacity and low wilting coefficient, that is, sandy or gravelly soils, may be more favorable to reproduction but less favorable to timber growth. Relatively high water-holding capacity and wilting coefficient are favorable if they are the result of humus rather than clay content, because although humus may withhold water to a considerable extent it increases permeability and fertility. It is seldom, however, that organic matter occurs in sufficient quantities below the upper foot of soil to be of appreciable importance in this region. In the Douglas fir and Engelmann spruce zones, the water-holding capacity and wilting coefficient are highest in the surface-soil samples, because of the presence of humus; but in the western yellow pine and lower zones the relation is usually reversed, because there humus is a minor factor and the clay content is greatest in the lower strata.

SOIL ZONES AS RELATED TO CLIMATE

As has been indicated in the preceding pages, the character of a soil is influenced in large degree by climate, through its influence upon the rate of disintegration of the parent rock, concentration of salts, leaching, and accumulation and decomposition of organic matter. The relation between climate and soils was studied in the

San Francisco Mountain region during the summer and fall of 1919 by J. O. Veatch,[17] assigned to this work by the Bureau of Soils. The results of Veatch's investigation have not been published, but the Bureau of Chemistry and Soils has kindly consented to the use of material from his report. The following discussion of soil zones consists of extracts from this report:

In the region outlined from the San Francisco Peaks down to the desert in any direction, embracing a range in altitude roughly of 8,000 to 10,000 feet, there is a great diversity in soil. As this can not be accounted for on a purely geologic or purely topographic basis, it is believed that the group characteristics of mature or old soils have been determined by climate. An attempt is here made to define the soils into broad groups or zones and to state the relation of each zone to certain elements of climate. The observation in mountainous regions that soils change with altitude and differences in precipitation is not new, but the attempt to establish limits for major groups of soils and to define those features which are determined by climate in contradistinction to those which are geologic is still somewhat in the nature of pioneer work in soil science.

In the San Francisco Mountain region, beginning at the lowest altitudes and in the region of least precipitation and highest temperature, the soils exhibit the lowest content of humus, this being practically absent and never sufficient to produce a pronounced brownish tint; the prevailing soil color is gray or else is inherited from the rock which constitutes the soil or from which the mineral base of the soil is derived. With increase in altitude, there is an increase in humus until the maximum thickness of humus and intensity of humus color are reached in an altitudinal belt ranging from 8,000 to 10,000 feet, thence there is again a decrease (ignoring in some instances a thick covering of forest mold consisting mainly of unhumidified organic matter) to the tops of the San Francisco Peaks. In both the highest and the lowest soil zones there is at best only a small supply of plant matter as a source of humus. In the desert, this is largely consumed by natural combustion or oxidation due to high temperatures and a very high percentage of sunshine; at the alpine heights the low temperature probably limits the activity of decomposing bacteria.

The changes in texture and structure with altitude and climate are analogous to those in humus. In both the desert and at alpine heights the soils in general may be described as psammogenous (characterized by a maximum content of coarse particles, sand, gravel, and stone, with a minimum of clay). Clay soils in both instances are practically absent except where purely geologic. Between the two extremes, pelogenous soils (those containing a high percentage of fine particles, clay and silt in size) are developed.[18] The maximum content of clay seems to be developed in a zone between 7,000 and 8,000 feet. Here temperature is sufficiently high and moisture sufficiently abundant for the decomposition of minerals into clay but without an excess of water which would cause leaching. Again the clay content in soils decreases with increase in elevation, so that at alpine heights the content of silt and clay is no greater than in the desert or at the lowest elevations.

The content of calcium carbonate and other alkaline salts is highest in the desert or belt of least precipitation and highest evaporation, with a gradual decrease in the percentage up to altitudes of 7,000 to 8,000 feet, where the amount of calcium carbonate is rarely sufficient to produce free effervescence with acid, and where the soils are nearly neutral in reaction. Although no laboratory investigations have been made, it would appear that there might be an increase in acidity, due to the formation of a spongelike or feltlike mold of semidecomposed plant matter, up to 11,000 to 11,500 feet, and a grayish or leached horizon directly beneath the mold.

Intensity of iron oxide coloring as a phenomenon of soil-forming processes seems to be greatest in a zone from about 6,500 to 8,000 feet. Here pro-

[17] VEATCH, J. O. SOILS AND THEIR RELATION TO CLIMATIC AND VEGETATIONAL BELTS, SAN FRANCISCO MOUNTAIN REGION, ARIZONA. Unpublished manuscript.

[18] The terms "psammogenous" and "pelogenous" were coined by Thurman, the Swiss investigator, whose writings are quoted in part by Schimper (*39, p. 101*). These terms, with slight modification of their original meaning, may be made to serve a useful purpose in regional descriptions of soils.

nounced reds and yellows in the subsurface horizon of the soil profile are observed. At higher elevations pale reds, and pale yellows, lavender, light grayish-chocolate, and lemon yellow are prevailing shades; below this middle zone down to the true desert, oxidation colors become gradually less intense until grayish soil color predominates. Both in the highest and lowest zones pronounced reds and other shades are present which are inherited from the rocks which furnish the mineral base of the soil.

Comparisons of the thickness of the soil cover or residuum of weathering may not be without value. The soil cover in the desert is less, other things being equal as nearly as possible, than at the intermediate elevations. The rather popular conception of arid soils as being of great thickness has been derived from observations on irrigated desert soils, which from the nature of things are generally situated in valleys and on terraces where the greatest thickness of wash or alluvium has accumulated, and in some instances the soil is practically synonymous with a geologic formation. Probably the greatest thickness of the soil proper is at 7,000 to 9,000 feet altitude, thence there is again a much smaller thickness near and above timber line.

Within an altitudinal range amounting to 8,000 to 10,000 feet six separate soil groups are differentiated. These are designated by geographic names for the purpose of convenience of reference and description. There is a blending of the features of one soil zone with the succeeding zone above and below, in conformity with the gradual change in climate and vegetation from one climatic and vegetational belt to another, so that within certain limits a line of division drawn on a map must necessarily be somewhat arbitrary. In general, however, fairly definite altitudinal limits can be given to the separate soil groups. However, soil types having the same essential characteristics may frequently be found considerably above or below the altitudes at which normally they would be expected. Were the slope an ideal one, that is with perfectly smooth surface and uniform gradient, these exceptions would not appear. They are due mainly to differences in topography and direction of slope as affecting the amount of moisture and temperature in the soil, as for example on steep north-facing slopes of canyons, say at an elevation of 6,500 feet, where a soil high in humus and low in lime, supporting a growth of western yellow pine, Douglas fir, and aspen may be found; although normally, high lime soils, supporting a growth of western yellow pine, piñon, juniper and semidesert shrubs are found at this elevation. Evaporation is a factor which has to be taken into consideration even where precipitation is the same. Peculiar local geologic conditions affecting the structure of the soil also account for these adventitious types. As for example on the slopes of cinder cones at 7,000 to 8,000 feet, soils frequently exhibit some of the normal characteristics of soils at 6,000 to 7,000 feet. The nature of the soil or rock is such that only very small amounts of water are held near the surface, and on account of the very open porous condition and lack of humus covering, there is a high percentage of loss through evaporation.

DESCRIPTION OF THE SOIL ZONES

In the region outlined, six separate soil zones are differentiated. These are designated by geographic names for convenience of reference and description. The plan of description here presented is original, and the names for the zones have not heretofore been used in soil literature.

NAVAJOAN ZONE

The Navajoan is largely desert; its altitude is generally below 5,500 feet. The climate is hot and semiarid, and the annual precipitation is less than 12 inches.

The soil profiles in general have the following characteristics: Grayish surface soil (the tints or colors of which are inherited from the rocks without appreciable change); very low or practically no humus content; high percentage of calcium carbonate and other easily soluble salts throughout; "caliche" (whitish layer of cementation, mainly by calcium carbonate,) at variable depths; and nearly uniform texture and structure above the caliche layer or above the unaltered geologic substratum, (the separate horizons being at most only obscurely marked). In this zone, the action of the climate is such that distintegration generally exceeds decomposition, so that the soil may be classed as psammogenous.

Moisture because of low precipitation, ordinarily descends to only a slight depth and is quickly transpired or lost directly through evaporation. Shallow soils are extremely dry; in deep soils the reservoir of moisture is in substrata lying at great depths.

It is not improbable that differences in soil characteristics between the most arid regions (such as are commonly termed desert) of the Colorado Plateau on the one hand and those of that physiographic region lying south of the plateau rim, embracing southern Arizona and most of southern New Mexico, are appreciable. The writer is inclined to group tentatively the most arid soils of the two regions separately, largely on the assumption that the differences in mean temperature and evaporation have affected soil differences. Limited observations in the two regions indicate that more intensive oxidation colors, with development of reddish ferric oxides, and higher percentages of silt and clay (geologic and topographic conditions being as nearly as possible the same) prevail in the southern region. The zone of most arid soils in the southern region is given the name Jornadan. Possibly the soils at the lower altitudes in the Verde River Valley just below the rim of the San Francisco Plateau should be included in the Jornadan zone.

UTAHAN ZONE

The Utahan zone corresponds in altitude to the piñon-juniper type; approximate altitudinal limits 5,500 to 6,500 feet; moderate temperatures; annual precipitation 12 to 15 inches.

The generalized profile of the Utahan zone shows the following layers: (1) A loose and finely granular grayish to pale-brownish surface layer; (2) a layer showing very slight clay concentration and slight cementation from soil salts; (3) a highly calcareous layer, drier and more friable than the layer above; and (4) the geologic substratum. The humus layer is very thin, and the content of humus is low, but in many places sufficient to produce light-brownish tints at the surface. The soils are moderately high in lime and mineral plant food from the surface downward. They are psammogenous for the most part.

COLORADAN ZONE

Corresponds to the western yellow pine type; altitudinal limits of the lower Coloradan approximately 6,500 to 7,000 feet and of the upper Coloradan 7,000 to 8,500 feet; cool climate; annual precipitation, much of which is snow, 18 to 25 inches.

The generalized profile of the Coloradan zone shows soil layers from the surface as follows: (1) Neutral or very slightly calcareous pale-brownish to chestnut-brown surface soils in which the humus color may frequently extend to a depth of several inches; (2) heavier-textured and less pervious subsurface layer, in which yellowish, brownish, and reddish oxidation colors reach maximum intensity; (3) a more friable layer (containing less clay than layer No. 2) in which there is a very low to moderately high content of calcium carbonate; and (4) geologic substratum.

This zone can be conveniently divided into upper and lower members. In the lower Coloradan, there is sufficient humification to produce only light brownish tints; the intermediate subsurface layer shows a slight cementation from soil salts; and the lower part of the soil profile is frequently highly calcareous. In the upper Coloradan zone there is sufficient true humus to produce brownish tints; but the climate is not sufficiently moist to permit an appreciable accumulation of plant mold or duff in forests. The intermediate layer is heavier in texture than the surface soil and frequently is notably stiff and compact but shows no great degree of cementation due to concentration of soluble salts. Soil colors due to oxidation of iron minerals reach maximum intensity in this zone. The soils are neutral or but slightly alkaline and apparently do not exhibit high percentages of lime in the form of carbonate in any part of the soil profile, though neither do they exhibit evidence of excessive leaching. They are high in fertility.

In the Coloradan zone, silt loam, clay loam, and clay are more common textures than in the two zones previously described; that is, the soils on the whole are pelogenous rather than psammogenous.

DATIL ZONE

The Datil zone corresponds to the Douglas fir type; altitudinal limits approximately 8,500 to 10,000 feet; cool humid climate with smaller range of temperature than in the Coloradan zone; annual precipitation, the greater part of which is snow, 25 to 30 inches.

The generalized profile of the Datil zone shows the following layers: (1) Thin covering of mold in forests, mild humus rather than acid; (2) comparatively thick brown or dark-brown surface soil, containing sufficient humus and organic matter to produce loamy texture; (3) layer heavier in texture than the surface soil but showing no cementation or notably stiff or compact condition; and (4) geologic substratum.

In the Datil zone, the process of humification has probably proceeded farther than in any other zone. Red soil color is less pronounced and less common than in the Coloradan zone. The content of lime carbonate is low, except where this is purely a geological phenomenon. In this zone, weathering agencies would be expected to effect a relatively greater amount of decomposition than in other zones, but locally the percentage of finer particles is perhaps no greater than in the Coloradan zone, because in this region most of the soil is derived from coarse alluvial wash and the bowlders of rock slides or avalanches.

AGASSIZ ZONE

The Agassiz zone corresponds to the Engelmann spruce type; altitudinal limits approximately 10,000 to 11,500 feet; colder than the Datil zone and precipitation slightly higher.

The layers in the generalized profile in the Agassiz zone are as follows: (1) Comparatively thick layer of mold, the plant matter showing very little humification and acidity; (2) an underlying humus layer, of low humus and very low lime content, and acid in reaction; (3) thin or very thin layer showing no evidence of considerable concentration or accumulation of clay, pale or obscure in color, and low in lime content; and (4) geologic substratum.

The forest soil is characterized by a thick feltlike covering of mold or accumulation of unhumidified plant matter, which is sharply separated from the underlying mineral soil. In many places the mineral soil for a half inch to 2 or 3 inches has a grayish, ashy appearance. The oxidation colors are pale or dull yellows and light browns. Probably less clay is formed under the weathering agencies which prevail than in the Datil and Coloradan zones. In the unforested areas or grass-covered glades, a loose, fluffy grass mold is present. The humus color here is darker or more pronounced than in the forest, and it may be reasonably inferred that more available nitrogen is present.

FRANCISCAN ZONE

The Franciscan zone coincides with the alpine vegetation zone above the upper limits of tree growth, which in the San Francisco Mountains is about 11,500 feet. The climate is alpine or boreal, and the region may be described as a cold or arctic desert.

The soils of the Franciscan zone represent an extremely thin cover over the hard rock. They can be described as psammogenous or containing extremely small percentages of silt and clay. Little or no change in texture takes place with depth, and the soils are very open, pervious, and nonretentive. Humus is present in very small quantities or is lacking, and the content of lime is very low. The color is likely to be inherited from the rock or to show only pale-yellow oxidation tints. In the region under consideration practically the only loose soil is in pockets or crevices in rocks or in protected situations under rock ledges. Otherwise the soil consists of the hard rock which may be barren, lichen-covered, or covered by a mossy or peaty accumulation.

RÉSUMÉ OF FINDINGS ON CLIMATE AND SOIL

The significant facts about the climate and soil which seem to have a bearing upon plant distribution in the Southwest may be summarized as follows:

Temperature falls generally with rising elevation, but this is not so evident in the mean or in the minimum as in the maximum. The best insight into temperature conditions is obtained from a detailed analysis of thermograph records, which show not only lower maxima but a much shorter duration of high temperatures in the high than in the low altitudes. Temperature summations and particularly the physiological indices of temperature efficiency bring out these relations in a striking manner.

Soil temperature follows the course of air temperature only in a general way; current changes in the two may be directly opposite. This relation is explained by the fact that the soil derives more of its heat directly from solar radiation than from the air. Surface soil maxima are often much higher than the air maxima. At depths of a foot or more both the maximum and the minimum are greatly tempered so that the diurnal fluctuations are reduced to 1° F. or less. Anything which affects the incidence of solar radiation upon the ground affects the soil temperature correspondingly. Thus, soil temperatures are distinctly lower in the shade of trees than in the open and on north than on south slopes.

Soil moisture is determined mainly by precipitation but is modified by the physical characteristics of the soil and by temperature, humidity, and movement of the air. Precipitation increases rapidly and uniformly with altitude up to the Douglas fir zone, beyond which the increase becomes less perceptible. Seasonal distribution is practically the same from desert to timber line in the same locality. Corresponding forest types receive slightly less precipitation in New Mexico than in Arizona, and there is also a noticeable difference in seasonal distribution. On an average, a given forest zone in New Mexico receives less precipitation in winter and more in May and June than the same zone in Arizona.

Physical composition of soils appears to affect plant growth much more than chemical composition. Deep, moderately sandy or gravelly soils are most favorable for all tree species. Clay soils are generally adverse to natural reproduction, but unless extremely heavy they favor good development of trees which have passed the seedling stage. Soils derived from granite, sandstone, and the acidic volcanic rocks are usually lighter and more permeable than those derived from limestone and basalt, although both the limestone and basaltic soils become fairly permeable when mixed with sand, gravel, or stones. Climate is probably fully as important as geologic origin in determining the depth and physical characteristics of a soil. This also applies to chemical characteristics in so far as they are modified by the influence of moisture upon soluble salts and by the influence of both heat and moisture upon the presence and decomposition of organic matter.

CHARACTERISTICS OF THE SPECIES

Much information regarding the habits of forest trees in the Southwest has been accumulated by many persons through years of observation. Although much of this is known to foresters, it seems desirable to bring together the most salient facts before any attempt is made to correlate physical conditions with distribution of species. In addition to this rather general information, the results of several recent experiments and systematic observations will be presented. Throughout this discussion the aim will be to stand the various species side by side, so to speak, and compare them with respect to all features on which information is available.

RELATIVE HEAT REQUIREMENTS

Heat requirement is too complex a question to be answered by observational methods. If one may judge by the temperatures prevailing where the principal conifers of the Southwest are found naturally, the order of the species with regard to heat requirement, beginning with the highest, is about as follows: One-seed juniper, Utah juniper, piñon, Arizona cypress, alligator juniper, western yellow pine, limber pine, white fir, Douglas fir, blue spruce, bristlecone pine, corkbark fir, and Engelmann spruce. In the following pages, observations and experimental data on the relative heat requirements of several species will be cited. Absolute requirements or, rather, the range of requirements presents another problem, which will be approached later.

FROST RESISTANCE

A phase of heat requirement which has received much attention in European forestry is resistance to frost. In a region where unseasonable frosts are so prevalent as in the mountains of the Southwest, this would seem at first thought to be a matter of very great importance. As far as native species are concerned, however, the frost problem seems to be fairly well met either by resistant qualities or by adjustment of distribution. None of our native species have been observed to suffer unduly from frost in their natural habitats; it is when they are taken away from home that they are likely to be injured. A large part of the frost damage reported in Europe is no doubt to be accounted for by the introduction of exotic species or by the artificial transplanting of indigenous species on naturally treeless sites. Douglas fir is an American species which is peculiarly subject to frost injury in Europe. In this country it appears to avoid frosty sites; the seedlings which start on such sites are either killed outright or are so severely injured that they can not compete with their neighbors. This species has been found to suffer severely from frost when planted in the western yellow pine zone at the Fort Valley station, where, although day temperatures are much higher than in the Douglas fir zone, night temperatures are likely to be lower. Blue spruce, under similar conditions, suffers to only a slight extent. Norway spruce and Scotch pine (Riga variety), both exotics, have been grown on the experiment station grounds since 1910 and have at no time shown appreciable effects of frost. Western yellow pine first-year seedlings have been known to be killed by fall frost on a few occasions. Observations in 1908 led the writer to surmise that this is a common cause of damage, but experience since then indicates that frost damage to western yellow pine in its native habitat is mainly to seedlings which germinate late in the summer. First-year nursery-grown seedlings of western yellow pine from seed collected on the Sierra National Forest of California were on one occasion completely killed by a November freeze, while plants from seed collected in Arizona, New Mexico, Colorado, and the Black Hills of North Dakota were uninjured.

TEMPERATURE RESPONSE

As has already been pointed out, observations in the field under many conditions and where several species are found side by side indicate that western yellow pine responds more slowly to the stimulus of rising spring temperatures than do Douglas fir, blue spruce, and white fir. Bristlecone pine likewise responds more slowly than corkbark fir and Engelmann spruce when the three appear on the same site. All the pines are able to go far above their usual upper limits by taking advantage of steep south slopes and ridges where the amount of heat available is probably higher than air temperatures indicate. This is especially true of bristlecone pine, which in the higher altitudes of this region occurs almost exclusively on south slopes and ridges, reaching up to 11,500 feet in elevation.

In the late fall of 1919, potted plants of western yellow pine, Douglas fir, bristlecone pine, and blue spruce taken from out of doors were placed in the greenhouse at the experiment station. No heat was applied, and the plants remained dormant until the latter part of February. From February 1 until March 20, the mean temperature fluctuated greatly, but the maximum rose above 75° F. on most days. The dates on which the buds began to open are as follows: Blue spruce, February 28; Douglas fir, March 12, and western yellow pine and bristlecone pine, March 22. On the experiment station grounds it has been observed year after year that the blue spruce and Douglas fir seedlings begin growth about a week earlier than western yellow pine.

The beginning of root growth in the spring has been observed in the experiment station nursery. Soil temperature was recorded with thermometers at a depth of 6 inches; in 1920 the cylinder of a soil thermograph was placed among the roots. Western yellow pine roots began to grow, as indicated by the appearance of white root tips, when the maximum (afternoon) soil temperature 6 inches below the surface rose to between 52° and 54° F. four days in succession. Bristlecone pine and Douglas fir began growing when corresponding temperatures reached 50° to 52° F. In May, 1914, blue spruce roots were growing vigorously when afternoon temperature ran up to 49° or 50° F., and western yellow pine roots showed no signs of activity.

In the spring of 1920 an experiment was carried out in the experiment station greenhouse with the object of comparing species as to rate of germination in low and relatively high temperatures. In the absence of facilities for maintaining a contemporaneous series of gradations in temperature, three lots of seeds were sown at different times, the first on February 19, the second on April 1, and the third on May 1. No artificial heat was used in the greenhouse, it being thought that the natural rise in temperature with the advancing season and increasing length of days would be sufficient to influence germination to a noticeable degree. During clear weather, even in winter, high temperatures are attainable under glass and a large proportion of this heat is retained at night; but when the skies are overcast, as they may be for several days at a time during winter storms, little heat is stored during the day, and night temperatures drop to a low point. An effort was made, by ventilation, to keep the maximum air temperatures below 90° F. and, by closing the greenhouse in the afternoon, to keep the minimum well above freezing. High maxima were avoided, but freezing or near-freezing temperatures were of rather frequent occurrence in March and April. The daily range was comparable to that of the western yellow pine type but was considerably higher than that which usually prevails in the Douglas fir and Engelmann spruce forests. Soil temperture was measured with an ordinary thermometer, the bulb of which was placed about one-quarter inch below the surface of the soil.

Western yellow pine, bristlecone pine, Douglas fir, and Engelmann spruce were represented in the test. All the seeds except Douglas fir, which came from the Santa Fe National Forest in 1916, were collected in the San Francisco Mountains in 1918 or 1919. Two hundred seeds of each species were sown in tills 1 foot square and 4 inches deep, filled with sandy loam. With the exception of the Engelmann spruce seeds, which on account of their small size were covered only one-eighth inch, the seeds were pressed into the soil and covered to a depth of one-quarter of an inch with clean sand sifted over the surface. Water was applied in the evening in quantities judged sufficient to keep the surface moist through the following day.

According to the temperature and germination curves in Figure 34, the four species differ markedly in their response to heat. Bristlecone pine germinated well throughout the range of conditions existing here. Douglas fir and Engelmann spruce did better in the cold period of March and April than in the warmer period following the May sowing. Whether the low germination of these species in the last test was due entirely to high temperature is doubtful. On hot days the surface soil becomes somewhat dry, and this, rather than heat, may be the adverse factor. Engelmann spruce in particular would feel the effects of surface drought because of the slight depth to which the seeds were covered. Douglas fir also would be affected more than the pines, because the seeds are light and tend to work to the surface of the soil. Western yellow pine shows a clear preference for high temperature. In the March sowing this species started off fairly well during the first 20 days, which were relatively warm, but fell off sharply in the succeeding cold period and rose again with rising temperatures in May. The April curve for this species rises gradually until about May 25 and then shoots up abruptly when the mean air temperature reaches the 60° mark.

The May curve begins to decline at this point, evidently because most of the seeds had already germinated.

RELATIVE LIGHT REQUIREMENTS

There is a divergence of views as to the part played by light in the growth of trees. Early silviculturists were inclined to ascribe to

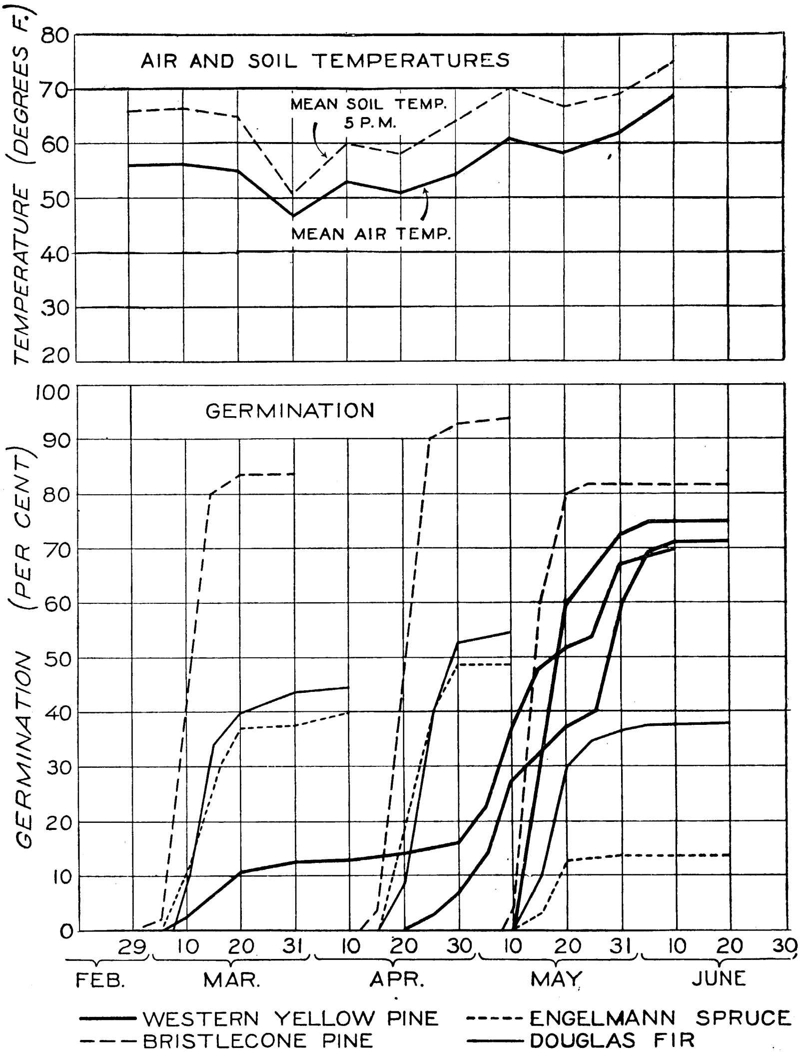

FIGURE 34.—Relation of air and soil temperature to germination in unheated greenhouse. Seed of four species sown February 19, April 1, and May 1, 1920

this factor every phenomenon which could be even remotely connected with it. Recent years have witnessed a swing toward the opposite extreme, some investigators now contending that light plays a relatively unimportant rôle. These more or less conflicting conclusions may be attributed in part to the absence of a uniform conception of what constitutes light and in part to the intimate and often confusing relation between light and other physical factors.

Sunlight is made up of rays or vibrations varying in wave length and in their capacity to act on matter. The rays of short wave length are characterized mainly by chemical activity and those of long wave length by thermal activity, although neither chemical nor heating effect is confined to any one set of wave lengths. Luminous energy is exhibited only by rays of intermediate wave length. This distinction, however, is an arbitrary one, as it is based not upon any peculiar characteristics of the light rays but upon the sensibility of the human eye. Technically, only those rays whose wave length is such as to produce the sensation of vision are termed light. These comprise only a small portion of the solar spectrum, including that in which photosynthesis is centered but omitting large portions of heat and chemical energy represented by the infra-red and the ultra-violet, respectively. Obviously it is desirable in dealing with plant life to broaden our conception of the term light so as to include the entire range of the solar spectrum.

The fact that relatively weak illumination has in some instances been found adequate for photosynthesis has led some investigators to assume that light is seldom a limiting factor in the forest. It should be borne in mind, however, that light in the broad sense is concerned in other activities, such as transpiration and respiration and a number of purely chemical reactions. Light of relatively short wave length, which is most susceptible to interception by the atmosphere and other obstructing agencies, exercises an important influence in developing proper form in plants. The extremely slender stems and otherwise abnormal characteristics assumed by some plants in greenhouses and in shaded situations outside is said to be due to a deficiency of short wave lengths.

Direct sunlight may also be needed as a source of heat. This applies especially if the air temperature is near the minimum for a species. Under such circumstances, seedlings under cover may suffer from lack of heat, notwithstanding the presence of adequate light for photosynthesis. That plants may derive an appreciable amount of heat energy from sunlight is indicated by experiments by Seeley (*40*), Matthaei (*28*), Blackman and Matthaei (*5*), Smith (*42*), and Ehlers (*16*), in which the temperatures of leaves of the same species were compared in the sun and in the shade. These investigations agreed in finding the leaves exposed to the sun generally hotter by several degrees than those in the shade, and not infrequently the excess in the leaves in the sun was as high as 15° C. In a few instances the leaves in the sun registered slightly lower temperatures than those in the shade. This may be attributed to excessively rapid transpiration in the leaves exposed to the sun. Ehlers (*16*) points out that because of the cooling of the leaf as a whole by rapid transpiration the temperatures recorded for leaves in the sun are probably considerably lower than those within the chloroplast. Matthaei (*28*) found evidence of photosynthesis in *Prunus laurocerasus rotundifolia* in air temperatures as low as −6° C. when exposed to direct sunlight and suggests that in conifers under strong insolation, photosynthesis may take place at still lower temperatures.

Abnormal development of seedlings in the shade of older trees is not always due to deficient light or heat. If both these factors are above the minimum for the species, it is well to look for other causes, either independent or contributory. Fricke (*17*) found that Scotch pine (*Pinus sylvestris*) seedlings of poor development under an old stand responded vigorously when freed from root competition by trenching. Toumey (*43*) obtained similar results with northern white pine (*P. strobus*) in New England. In 1923 the writer undertook to ascertain to what extent the same relations hold for western yellow pine in Arizona. Two plots of unthrifty seedlings shaded about two-thirds of the day by groups of mature trees were trenched to a depth of 18 inches. Although the taproots of young pines penetrate deeper, a strong system of laterals, which are confined largely to the upper foot of soil, constitute the main feeders. In order to prevent drying from the sides, the trenches were refilled, but they were subsequently opened at intervals of from one to two years in order to cut any roots which had entered from the outside. The seedlings were from 4 to perhaps 9 years old and from 2 to 12 inches tall when the records were begun. At the end of five years only 10 out of the original 26 plants remained. The survivors had grown to heights ranging from 7 to 26 inches. During 1928 the height growth was from 1.4 to 3 inches, as compared with 3 to 5 inches for seedlings of the same age in more open situations near by. These results indicate that although the seedlings have probably been benefited by the removal of root competition, insolation, be it light or heat, is surely an important factor in the growth of western yellow pine. This conclusion is in harmony with the common observation in the Southwest that western yellow pine seedlings grow closer to old trees on the south than on the north side. On the other hand, the fact that growth is usually below normal even on the south side indicates that root competition is also a factor.[19]

Open stands do not always indicate intolerant species, nor does the occurrence of young seedlings under cover prove that they are tolerant of shade. The woodland species of this region are widely spaced because the rainfall is not sufficient to sustain a dense stand or because fires have killed the young growth. The same is true in the western yellow pine type. Seedlings of *Juniperus monosperma*, *J. utahensis*, and *Pinus edulis* grow under and immediately around old trees, forming a characteristic clump or circle. They are able to live in this partial shade, but they require abundant sunlight for good growth. Although low evaporation, soil cover, and seed supply under old trees favor germination, seedlings also start in open situations. Utah juniper, particularly, is noted for its ability to invade wide open spaces. Western yellow pine germinates best in the shade of old trees, because of the favorable degree of moisture at the surface of the soil; but the seedlings which start in such situations seldom live more than four or five years. For normal development, they usually require direct sunlight during one-half to three-fourths of the day.

[19] Since the preparation of this bulletin a number of publications on the light requirements of forest trees have appeared. These and some of the older works have been reviewed by the writer (*36*).

In the Douglas fir and Engelmann spruce types are better examples of shade tolerance. Here are extensive dense stands in whose shade seedlings of Engelmann spruce, white fir, and corkbark fir persist for many years. This is a valuable asset, for wherever a break in the cover occurs new growth is already on the ground and has a decided advantage over species which must start from seed. Douglas fir is less tolerant of shade than its common associate, white fir, and for this reason is unable to hold its own against white fir and other tolerant species in old stands. After a fire, however, Douglas fir has the advantage because it withstands drought better and grows faster than its rivals. In the transition between the western yellow pine and the Douglas fir types, western yellow pine finds itself at the same disadvantage as Douglas fir in the higher altitudes. Here Douglas fir and white fir, both of which are more tolerant than western yellow pine, are able to reproduce and persist under the old western yellow pines and to hold the ground when the pines die.

LIGHT MEASUREMENTS

In 1908 and 1909 the writer attempted to ascertain the minimum light intensities under which the various conifers are found in apparently normal condition. The photographic method first applied in ecological work by Wiesner (*48*, *49*) and improved by Clements (*10*, *11*) was used. In brief, this method employs a strip of sensitized paper which may be exposed a section at a time. The amount of discoloration is assumed to be proportional to the product of time by intensity. By timing the exposure and comparing the discoloration with standards exposed to full midday sunlight the relative value of any reading is obtained. This method has been criticized because it measures only the rays of short wave length. It would obviously be better to measure separately the intensity of different parts of the spectrum; but this calls for laboratory equipment which can not well be employed in the field. On the whole, the photographic method is probably as good as any available for field use. In Table 25 are presented the values obtained near Flagstaff, Ariz. The condition of the seedlings corresponding to the various light intensities is indicated by the classifications suppressed, fairly vigorous, and thrifty.

TABLE 25.—*Light intensities as related to vigor of seedlings*

Species	Suppressed trees	Fairly vigorous trees	Thrifty trees
Utah (one-seed) juniper	----------	0. 328–0. 379	0. 500–1. 000
Western yellow pine	0. 028–0. 206	. 309– . 385	. 414–1. 000
Douglas fir	. 016– . 049	. 097	. 133– . 192
Corkbark fir	. 020	----------	. 028– . 068
Engelmann spruce	----------	----------	. 033– . 062

This subject has more recently been studied by Burns (*7*) under laboratory conditions. Potted plants were exposed in bell jars to pure white light emanating from two 750-watt nitrogen-filled electric bulbs. The light intensity was measured by means of a vacuum thermocouple. The activity of the plants was measured in terms of carbon dioxide absorbed from the air in the bell jar. When the percentage of carbon dioxide remained unchanged after an exposure of three hours, indicating that the amount used in photosynthesis was balanced by that given off in respiration, the light intensity was considered at a minimum for the plant in question. Of the 14 species tested by Burns, three, namely western yellow pine, Douglas fir, and Engelmann spruce, occur in the Southwest. The minimum light intensities under which these species were found to function normally are as follows: Western yellow pine, 30.6; Douglas fir, 13.6; and Engelmann spruce, 10.6. It will be seen that this order is the same as that given in Table 25.

Bates and Roeser (*4*) grew conifer seedlings from two months after germination to the age of 11 months in artificial light furnished by a 200-watt tungsten-filament, blue-glass lamp. The theoretical minimum light in which growth could be made, expressed in percentage of full sunlight, is given for six Rocky Mountain species as follows: Engelmann spruce, 1.1; Douglas fir, 1.5; western yellow pine, 1.8; lodgepole pine, 2.4; limber pine, 2.7; and piñon, 6.3.

RELATIVE MOISTURE REQUIREMENTS

ROOT SYSTEMS

The root habits of several species have been observed in the forest and in nurseries. Western yellow pine, Douglas fir, corkbark fir, blue spruce, and Engelmann spruce rank in depth of roots about in the order named. Western yellow pine has a deep taproot with long laterals, suggesting an adaptation to the necessity of obtaining moisture from a large volume of relatively dry soil. The spruces and firs, both in the forest and in the nurseries, develop relatively shallow but very compact root systems, evidently adapted to intensive utilization of the moisture in a small mass of soil. Douglas fir exhibits characteristics intermediate between the western yellow pine and the spruces and true firs. Piñon and alligator juniper show extreme development of the open though not always deep type of root, and this is equally characteristic of the limber pine and bristlecone pine in the few specimens examined. Arizona cypress develops a deep but fairly compact root system. Root pruning and transplanting encourage profuse branching in the roots of the spruces and Douglas fir, and, in less degree, in western yellow pine and Arizona cypress. Piñon, alligator juniper, and bristlecone pine respond still less to this treatment. Whether dry soil would induce the spruces and firs to develop a more open and extensive root system is not known. Observations made on full-grown trees indicate that the root habits exhibited in the seedling stage are to a large extent retained in after life. Engelmann spruce in typical stands has a compact, shallow, circumscribed root system. In open stands the laterals are more extensive, but in dense and open stands alike they seldom reach below a foot in depth. Western yellow pine roots reach depths of 6 or more feet in porous soils; on stiff clay soils they seldom go below 3 feet. In open stands laterals reach out 100 feet, but in dense even-aged stands they probably go but little beyond the spread of the crown.

TRANSPIRATION AND WILTING COEFFICIENT

Transpiration provides a measure of the rate of water consumption; wilting coefficient, or the moisture content of the soil when a plant wilts, indicates the capacity of the plant to remove water from the soil particles or the ability of the soil to withhold it. During 1919 and 1920, western yellow pine, Douglas fir, bristlecone pine, and blue spruce were compared with respect to both those functions.

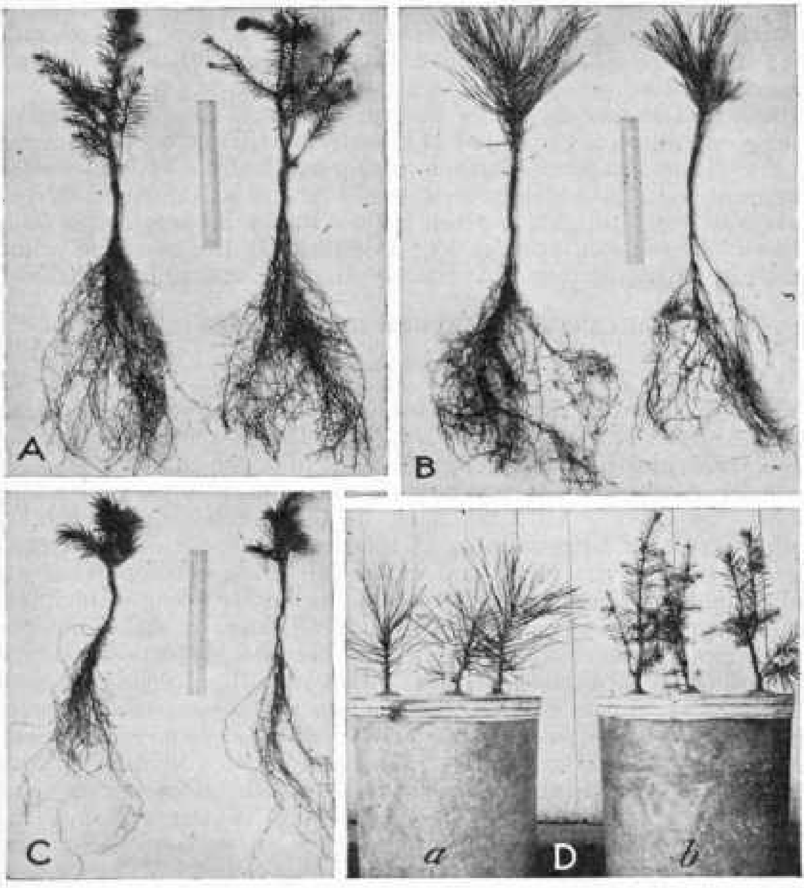

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FIGURE 35.—A, Douglas fir (4 years old) after two years in pots; B, western yellow pine (4 years old) after two years in pots; C, bristlecone pine (6 years old) after two years in pots; D, western yellow pine (*a*) and Douglas fir (*b*) in sealed pots for transpiration tests

Blue spruce was included under the misapprehension that it was Engelmann spruce, an error which was not discovered until the experiment was finished. Nursery-grown seedlings from 2 to 5 years old were planted in galvanized-iron pots (fig. 35, D) 10 inches deep and 9 inches in diameter. Three plants were placed in each pot. Metal covers were used, and all openings through which rain might enter were sealed with surgeon's tape or art clay. After each weighing, water was added until the weight of each pot was restored to a value corresponding to a moisture content about 11 per cent above wilting coefficient. It is realized that this added water was not evenly distributed through the soil mass. During the growing season the plants were out of doors at the control station, and during the remainder of the year they were kept in an unheated greenhouse. In view of the fact that this experiment has previously been described (*35*), only the most essential facts will be related here.

For the purpose of this experiment it seemed preferable to refer water losses to increment in dry weight rather than to area of leaf surface. Table 26 indicates that the highest ratio of transpiration to accretion is in bristlecone pine, followed in order by western yellow pine, Douglas fir, and blue spruce. Except for the relative positions of western yellow pine and bristlecone pine, these results agree in a general way with those obtained by Bates (*1*) in Colorado. Because of the small number of plants used, the divergence between pots of the small species, and the small difference between average values for the several species, however, too much significance should not be attached to these relationships. It is readily conceivable that the addition of several pots in any group might still further reduce the margin of difference or even change the present order. For instance, western yellow pine No. 213 is higher than bristlecone pine No. 207, and if western yellow pine No. 213 were omitted, this species would average less than Douglas fir. A preliminary series with a smaller number of plants in 1918 and 1919 placed the species in an order almost the reverse of that of the 1919–1920 test. It is evident that in order to obtain reliable data the experiment should be conducted on a more extensive scale.

TABLE 26.—*Transpiration, and effective water use of different species of trees in relation to accretion in dry weight* [1]

Species, pot No., and age when potted	Dry weight		Transpiration, 1919 and 1920 [3]	Water used per gram of accretion
	Initial [2]	Accretion during two years		
Bristlecone pine:	*Grams*	*Grams*	*Grams*	*Grams*
207 (5 years)	7.66	19.89	8,186	412
208 (5 years)	5.42	13.78	6,465	469
Average 6 plants				440
Western yellow pine:				
204 (3 years)	6.03	30.25	11,219	371
205 (2 years)	2.55	16.69	6,469	388
213 (2 years)	2.87	22.83	9,771	428
Average 9 plants				396
Douglas fir:				
209 (4 years)	8.76	29.06	10,895	375
210 (4 years)	11.07	27.61	10,672	387
Average 6 plants				381
Blue spruce:				
212 (4 years)	7.14	15.51	5.478	353
215 (4 years)	7.83	31.33	11,445	365
Average 6 plants				359

[1] Since each pot contained three plants, all values are for three plants.
[2] Computed from ratio of dry to green weight of similar plants.
[3] Transpiration recorded only for July 1–Oct. 3, 1919, and Mar. 3–Sept. 1, 1920.

Table 27 gives the wilting coefficient for the same four species in two kinds of soil. The plants in the stony clay loam are the same as those used in the transpiration work, with several additions. As is to be expected, the soil to which sand was added has a much lower wilting coefficient than the clay loam. The results, however, indicate no large or consistent differences in the ability of the different species to extract moisture from the soil. This is in accord with the conclusion of Briggs and Shantz (*6*). Korstian (*23*), on the other hand, found the highest sap densities and, hence, the strongest pull on soil moisture in the species which occupy the driest sites. Thus, in Utah juniper osmotic pressures ranged from 15.9 to 28.2 atmospheres, whereas in Engelmann spruce the range was from 10.2 to 19.0 atmospheres. These conclusions are not necessarily in conflict, because Korstian's results were obtained from trees growing under a wide range of conditions and it is not unlikely that juniper and spruce in the same environment would exhibit similar sap densities.

TABLE 27.—*Wilting coefficient of different species of trees in natural and prepared soil*

Species	In stony clay loam [1]			In prepared soil (one-half clay loam and one-half sand)		
	Pots	Plants	Wilting coefficient	Pots	Plants	Wilting coefficient
	Number	*Number*	*Per cent*	*Number*	*Number*	*Per cent*
Bristlecone pine	4	10	10.56	2	2	6.35
Western yellow pine	4	8	10.55	5	7	5.80
Douglas fir	4	10	10.30	4	4	6.26
Blue spruce	1	3	10.25	3	3	6.03

[1] The pots in Table 26 form a part of this series.

In the course of a wilting test, interesting reactions of seedlings to the drastic reduction of soil moisture were observed. (Fig. 36.) On August 10, 1920, watering was discontinued in pots of western yellow pine, Douglas fir, bristlecone pine, and blue spruce, which prior to that time had been maintained at a moisture content of about 20 per cent, or approximately 9.5 per cent above the wilting coefficient for the soil in question. The rate of transpiration began to fall soon after,[20] and at the end of a month it was in most cases less than 3 per cent of the original rate. In the meantime the soil moisture had fallen to points varying from 0.2 to 0.5 per cent above the wilting coefficient. During the next two months, transpiration was almost imperceptible; plants of all species showed signs of weakening, as was indicated by change of color and drying of some of the leaves, but they did not have the appearance of wilting. With the approach of snow and cold weather in the latter part of October, all the pots were placed in the greenhouse. A change in mean temperature from 32° to 54° F. brought no appreciable response in transpiration. In order to ascertain whether the plants were really

[20] The gradual decline of transpiration here shown differs from the results of Veihmeyer, who found that in young prune trees the consumption of water was independent of soil moisture as long as it remained above wilting coefficient (*45*).

living, two pots containing western yellow pine were watered on November 13, restoring the average moisture content to 20 per cent. Immediately the transpiration rate shot up to the level maintained before the water supply was cut off, and new shoots appeared the following March. No species other than western yellow pine was watered.

No definite conclusions could be drawn regarding the relative persistence of different species, except that bristlecone pine seemed to surpass all the others. In some cases, the variation among individuals of the same species equaled that between the species. The important fact brought out in this experiment is that all four species

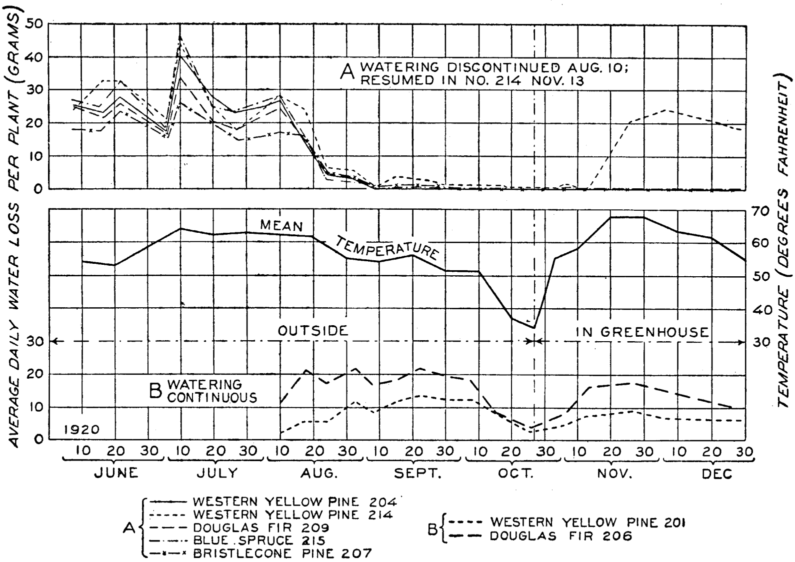

FIGURE 36.—Effect of soil moisture on transpiration, as shown by the behavior of typical pots of each species. All plants were moved from outside to the greenhouse October 27

apparently possess a great capacity for checking transpiration when the water supply is reduced to a dangerously low level.

WINTERKILLING

The generally accepted explanation of winterkilling is that the water in the soil surrounding the roots freezes and becomes unavailable. According to Kihlman (*22*), this condition, known as physiological dryness, takes place when the temperature of the soil water falls to about 34° F. If atmospheric conditions are such as to favor transpiration when the roots are unable to absorb moisture from the soil, the aerial portions of the plant tend to dry out. If this relation continues over a long period, the leaves and even the stems die. Winterkilling is favored, especially on bare ground, by extremely low night temperatures, high winds, and warm sunny days.

In the Southwest conditions causing winterkilling are most prevalent in the western yellow pine zone. In the winter of 1922–23, groups of western yellow pine saplings 3 to 4 feet high on a steep north slope near the Fort Valley station suffered severely, about 5 per cent of the trees being killed outright. On a gentle southwesterly exposure in the vicinity, the damage was appreciably less. During the same winter, large trees on an entire north hillside suffered to the extent that the leaves turned brown and caused the trees to appear dead. In June, however, practically all the trees took on new foliage. In the winter of 1924–25 saplings on a southerly exposure suffered more than those on a near-by north exposure. It can not be said from the observations made that any exposures are generally worse than others, for other conditions enter too largely into the situation. South slopes, it is true, thaw out more quickly than north slopes, but they are also more subject to evaporation. Sometimes the soil on south slopes in low altitudes may become actually dry in winter.

The piñons and junipers occasionally suffer from winterkilling in their natural environment but usually only when they occur above the normal range. Atmospheric conditions in the piñon-juniper zone favor rapid transpiration in winter, but the soil seldom remains frozen during long periods.

In the Douglas fir and Engelmann spruce zones of this region winterkilling is almost unknown, except where the trees are exposed to extremely high wind movement. Even there it is not certain whether the damage is due primarily to water loss or to mechanical action. Seedlings up to 4 feet high are usually protected by snow. Soil temperatures remain at dangerously low levels much longer than they do in the western yellow pine zone, but the cold air and low wind movement, except on exposed sites, are not conducive to high transpiration. An even temperature, less extreme in heat and cold than is found in the western yellow pine type, is favorable. Seedlings and transplants of Douglas fir in nurseries below the altitudes of continuous snow are usually a total loss if not protected in winter.

In the higher altitudes, exposed situations such as prominent ridges and steep south slopes are occupied almost exclusively by limber pine or bristlecone pine. These situations undoubtedly present severe conditions with respect to winterkilling. Evaporation is high because of high insolation and exposure to dry winds, and yet the night temperatures are low enough to freeze the soil to considerable depths. As shown by the planting experiments to be described, limber pine and bristlecone pine are the only species, with the possible exception of western yellow pine, that can withstand the winters on these sites.

Considered in their native habitats, the species or groups of species may be ranked with respect to liability to winterkilling about as follows: Western yellow pine, junipers, piñon, Douglas fir, spruces, true firs, limber pine, and bristlecone pine. The indications are that if all were subjected to equally trying conditions of frozen soil accompanied by relatively high evaporation, Douglas fir would head the list in liability to winterkilling and would be followed closely by the true firs and spruces and that the pines and junipers would show relatively greater resistance.

Shreve (*41*) reports a form of winterkilling among desert plants which appears to be caused by long periods of freezing temperature, irrespective of frozen soil or physiological dryness. Thus, he finds that the giant cactus (*Carnegiea gigantea*) succumbs when the temperature remains continuously below 32° F. for more than 18 hours. It is surmised that some of the observed damage in piñon and juniper may be of this nature. Broad-leaved trees, when planted in the western yellow pine zone, are also subject to a form of winter-killing which seems unrelated to soil moisture.

GROWTH PERIODS

During the three years in which climatological records were maintained in the San Francisco Mountains, weekly observations were made on the progress of growth, flowering, and maturing of seed. If all species were to respond equally to the stimulus of heat, one would expect the date of the beginning of growth to recede with altitude, in conformity with the temperature curve. In practice it is difficult to reduce the data on this subject to absolute terms for the purpose of comparison, because conditions vary on different sites and the growth habits of different species and even individuals of the same species are dissimilar. As far as possible, the species are compared on similar exposures and soils. This, however, is not always possible. For example, Engelmann spruce and Douglas fir in this region grow on much lighter soils than those prevailing in the western yellow pine zone. Typical stands of Engelmann spruce are restricted almost entirely to northerly exposures, and limber pine and bristlecone pine prevail on southerly exposures.

The beginning of growth in western yellow pine is marked by rapid elongation of the buds with the first warm days in May. If warm weather continues, the shoots grow steadily until about July 1, when elongation falls off and soon ceases. More frequently, however, the first growth is halted for several weeks by cold weather, and active growth is not resumed until June. Under these circumstances it is often difficult to fix a date for the beginning of active growth. In the pines the new shoots push out rapidly, but the new leaves do not develop until shoot elongation is almost finished. In the spruces and firs, leaves and stems develop simultaneously, the stems elongating rather gradually with the result that growth early in the season is less conspicuous than in the pines.

Table 28 presents, for the purpose of comparison, approximate dates of plant activities in different forest types. According to this table, the beginning of all vegetative activities is retarded with a rise in altitude, but the high-altitude species mature their seed earlier than those in the lower altitudes. In other words, the growing season is shortened at both ends as we ascend. The dates do not attempt to cover the extreme but rather the middle range of each species. In all species growth begins noticeably earlier at the lower than at the upper limits of the range. Opportunities are sometimes afforded for comparing two or more species on the same site. Under these circumstances, the one which normally grows in the coldest climatic zone is usually farthest advanced. Exceptions are limber pine and bristlecone pine, both of which are later than their immediate associates and little, if any, earlier than species of the next lower climatic zone. When found side by side, Douglas fir and white fir are earlier than western yellow pine, but limber pine is not appreciably earlier except in maturing seed. Engelmann spruce and corkbark fir are both decidedly ahead of bristlecone pine.

TABLE 28.—*Approximate dates of various plant activities in the different forest types*

Plant activity	Western yellow pine	Douglas fir	Limber pine	Aspen
Vegetative buds swelling	May 1-15	May 15-30	May 15-30	May 10-30.
Vegetative buds elongating or opening.	May 15-25	June 1-15	June 5-20	May 20-June 10.
Shoots making rapid growth	June 10-30	June 15-30	June 15-30	
Leaves coming out	June 15-July 30	June 10-20	June 10-20	June 5-15.
Shoot growth ceased [1]	July 1-10			
Staminate buds appearing	May 20-31	June 1-15	June 1-10	
Pollen falling	June 10-20	June 20-30	June 20-30	
Cones full grown	Sept. 15-30	Sept. 5-20	Sept. 5-20	No seed.
Seeds mature	Oct. 1-20	Sept. 10-30	Sept. 10-30	Do.
Leaves falling	Oct. 1-30	Oct. 1-30	Oct. 1-30	Oct. 10-30.
Period of active growth	May 15-Sept. 20	June 1-Sept. 25	June 5-Sept. 10	May 20-Sept. 10.

Plant activity	Bristlecone pine	Corkbark fir	Engelmann spruce
Vegetative buds swelling	June 1-20	June 1-15	June 10-20.
Vegetative buds elongating or opening	June 20-30	June 15-20	June 20-30.
Shoots making rapid growth	July 1-30	June 20-July 15	July 1-20.
Leaves coming out		June 20-30	June 20-30.
Shoot growth ceased [1]			
Staminate buds appearing	July 1-10	June 10-20	June 10-20.
Pollen falling	July 20-Aug. 20	June 20-30	June 25-July 5.
Cones full grown	Sept. 10-20	Sept. 1-20	Sept. 1-20.
Seeds mature	Sept. 20-Oct. 10	Sept. 10-Oct. 1	Sept. 15-Oct. 10.
Leaves falling	Oct. 1-30	Oct. 1-30	Oct. 1-30.
Period of active growth	June 20-Sept. 20	June 15-Sept. 10	June 15-Sept. 10.

[1] No definite data on species other than western yellow pine, but growth is practically over by the end of July, except in aspen.

Observations on the beginning of root growth have been made only on planted specimens at the experiment station. Western yellow pine is later than Douglas fir, blue spruce, and bristlecone pine. All species covered by the observations begin root growth about the time the buds begin to swell, a month or more before the bud scales burst. This fact is of great importance in relation to artificial reforestation. It points to the advantage of early planting in order to give the roots opportunity to begin functioning before new shoots and leaves are put forth.

FREQUENCY OF SEED CROPS

The idea prevails that seed crops are produced at somewhat regular intervals, fixed for each species. No definite periodicity has been observed in the San Francisco Mountains, except that limber pine rarely and bristlecone pine never has been known to fail. The nearest one can come to stating an average figure is to say that limber pine and bristlecone pine bear a good crop of seed nearly every year and the other species every two or three years. The quantity and quality in any year are evidently determined largely by external conditions such as frost and insects. Sometimes climatic effects are local, but at other times they are widespread. In some years western yellow pine has failed, while Douglas fir and Engelmann spruce in the same locality but at higher altitudes have borne prolifically.

In 1923 all species throughout the Southwest appear to have borne a good crop, whereas in 1924 failure was general except for bristlecone pine. In 1918 western yellow pine bore a phenomenal crop over most of the Colorado Plateau and practically throughout Arizona and New Mexico; yet one area within 2 miles of a heavy-yielding district bore only a light crop, and in another locality 15 miles distant there was an almost total failure.

As a rule all species in the San Francisco Mountains fruit sparingly and at infrequent intervals at the upper limits of their range. Observations on this point are confirmed by the absence of dense cone litter usually present in the optimum zones. Western yellow pine, Douglas fir, piñon, and the junipers bear prolific seed crops at the lower limits of their range, except that western yellow pine under these conditions is susceptible to the attack of a cone beetle (*Conopthorus ponderosae*).

RATE OF GROWTH

A comparison of the different species as to rate of growth under natural conditions calls for recognition of variations in site and climate. To determine the relative efficiency of different species as to wood production, they should be grown under the same conditions or at least under conditions in which all factors affecting growth are definitely known. When several species occur in association on the same site, as they do in many places in the Southwest, it is difficult to ascertain how much space each occupies. The site may be optimum for one species and near the minimum for another. Perhaps the fairest comparison of species is to take each in the environment best suited to it.

GROWTH OF INDIVIDUAL TREES

Distinction should be made between the growth of individual trees and the growth of stands. Wide annual growth rings are often due to open spacing and thus may not be an index of production per unit of area. Tables 29 and 30 give the diameter and height growth of average trees of different species in different localities. These figures are not to be regarded as representative of the various national forests but rather as indicating the range of growth under different conditions. It is evident that the so-called woodland species are much slower growing than the saw-timber species. Where western yellow pine and the woodland species come together in the transition zone between their respective types, western yellow pine shows distinct superiority in the rate of growth. In studies of several species on the same site in the transition between the western yellow pine and Douglas fir zones western yellow pine usually has a slight margin over Douglas fir; both exceed limber pine, white fir, and Engelmann spruce but are outstripped by blue spruce up to an age of 140 years. The shade-enduring spruces and firs may attain great age for their size because they have persisted many years in a state of partial suppression during the seedling and sapling stages and recuperated when released. Western yellow pine succumbs more readily to suppression, and therefore trees of this species are more likely to show the expected relation between age and size.

TABLE 29.—*Diameter of various species at different ages in national forests of Arizona and New Mexico*

Species and national forest	20 years	40 years	60 years	80 years	100 years	120 years	140 years	160 years	180 years	200 years	250 years	300 years
	Inches	*Inches*	*Inches*	*Inches*	*Inches*	*Inches*	*Inches*	*Inches*	*Inches*	*Inches*	*Inches*	*Inches*
Emory oak [1] coppice (Coronado)	3.5	7.9	12.3	16.2	19.6	22.6	25.5					
Piñon (Santa Fe)		.9	2.2	3.6	4.8	6.0	7.0	7.8	8.5	9.0		
Utah juniper (Tusayan)	1.2	2.4	3.8	5.2	6.6	8.0	9.3	10.4	11.4	12.4		
Rocky Mountain juniper (Santa Fe)			.9	2.4	3.9	5.3	6.4	7.4	8.0	8.5		
Western yellow pine (Apache) [2]	2.0	4.6	7.4	9.9	12.2	14.4	16.3	18.1	19.7			
Do [3]	1.3	3.4	6.0	9.0	12.0	14.8	17.5	20.0	22.4	24.7	29.8	33.5
Western yellow pine (Tusayan)	1.8	5.2	8.4	11.1	13.2	15.0	16.6	13.0	19.3	20.6	23.8	
Western yellow pine (Prescott)	4.0	11.4	16.8	21.0	24.0	26.2	27.6	28.6	29.4	30.0		
Western yellow pine (Sitgreaves)			11.2	14.7	17.7	20.2	22.1	23.8	25.2	26.4	28.3	
Western yellow pine (Gila)	1.0	6.8	11.2	14.8	17.6	19.8	21.5	22.9	23.8	24.7		
Western yellow pine (Crook)	3.0	8.1	13.6	17.7	20.1	22.6	25.2	26.7	28.4	29.5		
Western yellow pine (Carson)	.7	3.1	6.5	9.3	11.4	13.0	14.3	15.6	16.8	18.1	21.3	24.5
Douglas fir (Apache)	1.4	3.4	6.0	9.0	12.2	15.6	18.8	22.0	25.0	27.7	33.1	37.2
Douglas fir (Crook)	1.9	8.9	13.4	17.2	19.8	22.4	25.0	27.6	30.3	31.9		
Douglas fir (Gila)		5.2	9.0	12.6	15.7	18.7	21.5	24.3	27.2	29.0		
Douglas fir (Carson)		2.3	4.9	7.3	9.6	11.7	13.5	15.3	17.4	20.0	26.0	
White fir (Crook)	1.8	7.0	11.2	14.4	17.8	20.2	22.2					
White fir (Carson)		1.7	4.2	6.9	9.1	10.9	12.2	13.5	14.8	16.2	19.6	
Limber pine (Crook)	1.0	5.0	8.7	11.5	13.7	15.5	17.0	18.3				
Blue spruce (Apache)	1.1	3.8	9.2	14.8	18.4	21.0	22.8					
Engelmann spruce (Crook)		3.0	6.6	10.2	13.1	15.2	16.7	18.3	19.8			
Engelmann spruce (Carson)		2.1	4.9	8.3	10.9	13.1	14.9	16.4	17.7			
Alpine fir (Carson)		2.0	4.9	8.3	10.8	12.8	14.2	15.4	17.1			

[1] Diameters on stump for oak, piñon, and juniper; others 4½ feet above ground.
[2] Western yellow pine type.
[3] Douglas fir—western yellow pine transition.

TABLE 30.—*Height of various species at different ages in different forest types of Arizona and New Mexico*

Species and national forest	20 years	40 years	60 years	80 years	100 years	120 years	140 years	160 years	180 years	200 years	250 years	300 years
	Feet	*Feet*	*Feet*	*Feet*	*Feet*	*Feet*	*Feet*	*Feet*	*Feet*	*Feet*	*Feet*	*Feet*
Emory oak coppice (Coronado)	16	26	32	37	42	45	49					
Piñon (Coronado)	2	6	10	14	16	18	20	22	23	24		
Utah juniper (Coronado)	4	7	10	13	14	15	16	17	18	19		
Rocky Mountain juniper (Coronado)	1	4	7	10	13	15	16	17	17	17		
Western yellow pine (Apache)					49	60	64	69	73	76	82	86
Do.[1]	5	14	26	40	54	66	75	83	90	96	106	111
Western yellow pine (Tusayan)		27					83	90				
Western yellow pine (Carson)	5	21	38	48	53	57	60	62	65	68	75	81
Western yellow pine (Prescott)		31										
Douglas fir (Apache)	4	15	30	45	57	69	79	87	94	101	112	116
Douglas fir (Carson)		16	34	46	54	60	64	68	72	77	88	
White fir (Carson)		8	18	30	41	49	55	60	65	69	76	
Blue spruce (Apache)	4	14	34	58	78	92	104					
Engelmann spruce (Carson)		14	30	49	62	72	78	82	86			
Alpine fir (Carson)		11	27	46	58	69	76	83	88			

[1] Douglas fir—western yellow pine transition.

The wide variation in growth rate of the same species within its normal range affords an interesting subject for investigation. Western yellow pine on the Prescott and Crook National Forests grows much more rapidly than on the Coconino, Tusayan, and Carson. Douglas fir, Engelmann spruce, and white fir all maintain more rapid growth on the Crook and Lincoln than on the Carson. Unfortunately, climatological records are available for only a few of the sites concerned. As a rule, growth of all species is more rapid in the small mountains rising abruptly from the desert in southern Arizona and New Mexico than in the larger mountain masses rising from high plateaus in the central and northern parts of the two States. Indications, including the few available weather records, point to a combination of higher temperature and higher precipitation in corresponding forest types of the southern than of the northern mountains. Another favorable condition in the mountains of southern Arizona and New Mexico is that the soil is nearly everywhere permeable, in contrast with the heavy soils which are more or less common in some sections farther north.

GROWTH OF STANDS

A more adequate expression of growth is furnished by the volume of stands in relation to age. Mean annual growth per acre is readily determined from the age, volume, and area of even-aged, fully stocked stands. Unfortunately, few southwestern forests are even aged, and almost none are fully stocked. Another element of error in calculating mean annual increment is the fact that even though a stand may be fully stocked at the present time, no record is available of the trees which once grew and disappeared. The best stands of all species are rather dense in youth, and there is a gradual thinning through competition as age advances. In western yellow pine this thinning is fairly rapid, but in Engelmann spruce and to a less extent in Douglas fir the struggle for space is prolonged, and stagnation often results. In some Engelmann spruce stands observed at the age of 80 years, there were about 2,000 trees per acre of uniform height, all about 4 inches in diameter and with almost indistinguishable annual rings. When the deadlock is finally broken, the survivors will show a very low rate of growth and a considerable volume, represented by their vanquished rivals, will have been lost.

In the best mature stands as they occur over areas of a section or more, the yields for western yellow pine are about 20,000 board feet, for Douglas fir about 40,000 board feet, and for Engelmann spruce about 30,000 board feet per acre. Average yields, because of understocking, seldom attain more than half of these values. Selected, fully stocked plots of western yellow pine at the age of 200 years often yield as much as 40,000 board feet per acre. Corresponding yields in Douglas fir and Engelmann spruce ran up to 60,000 feet.

In forest practice it is less important to know the relative maximum rate of growth of different species than to know what a certain species may be expected to do under a given set of conditions. The three major commercial species in the Southwest, namely, western yellow pine, Douglas fir, and Engelmann spruce, attain their best development under distinctly different conditions, and only in the transition zones between forest types is there a question as to which species will make the best growth. In these zones the choice of species calls for a definite knowledge of growth habits and requirements.

CORRELATION BETWEEN PHYSICAL CONDITIONS AND THE DISTRIBUTION OF SPECIES

It may be assumed that in a broad way the distribution of species within a locality is governed by climate, soil, and biotic factors. It is reasonable to suppose that over long periods of time every species growing in a locality should become more or less abundant on all sites congenial to its existence. This, however, does not take into account more or less temporary disturbing elements such as fire, disease, insect or rodent epidemics, and the interference of man, any of which may practically eliminate a species from more or less extensive areas during limited periods of time. There is also a possibility that the absence of a species from a given site may be due to some adverse factor which operates only during the seedling stage, usually the most critical period in the life of a tree. Inability to compete with other species is sometimes thought to account for the absence of certain "intolerant" species such as western yellow pine on sites better suited to more "tolerant" ones, such as spruce. The many clues to these problems furnished by nature have been supplemented by an experiment started in 1917, in which several species of native conifers were planted in each of the forest zones above the woodland.

PLANTING EXPERIMENTS

The species used in the planting experiment were western yellow pine, Douglas fir, limber pine, and bristlecone pone, and also blue spruce which was thought at the time of planting to be Engelmann spruce. The western yellow pine stock was grown in the experiment station nursery from the seed collected on the Coconino National Forest. The Douglas fir and blue spruce came from the Gallinas nursery on the Santa Fe National Forest in northern New Mexico. This forest was also the source of the seed. The limber pine and bristlecone pine were grown at the Fremont laboratory of the Rocky Mountain Forest Experiment Station in Colorado, presumably from Colorado seed. The stock used comprised fully developed nursery-grown transplants from 3 to 5 years old, having well-developed roots from 8 to 12 inches long extending well below any dry surface layer resulting from drought of short duration. Planting was in accordance with the best practice developed at the Southwestern Forest and Range Experiment Station. With the exception of the limber pine-bristlecone pine site, all the planting areas were fenced against grazing animals.

Those who are accustomed to thinking of planting results in terms of the average survival of large numbers will be reluctant to accept conclusions based upon the small numbers of plants employed in this experiment. It should be borne in mind, however, that the main concern here was not the percentage of survival but ability to survive at all. For this purpose five plants properly handled should give more reliable data than several hundred under less careful treatment.

Although survival and size are the only factors capable of quantitative expression, equal significance is attached to the diagnosis of signs of abnormality as observed from time to time.

In all forest types in this region above the woodland, soil moisture is usually abundant below a depth of 5 or 6 inches until the first of June. (Table 21 and figs. 28 and 29.) In the Douglas fir and Engelmann spruce zones the moisture content remains high even through June. With favorable moisture and temperature, growth begins about June 1 in the western yellow pine type and from one to three weeks later in the Douglas fir and the Engelmann spruce types. If the soil becomes too dry later in the summer the new growth is the first to wilt, and if the drought continues the entire plant dies. Young shoots of Douglas fir and blue spruce may wilt when the roots are fairly well supplied with moisture, thus indicating either that these species have a low capacity for absorbing and transporting water or that the young tissues transpire at an excessive rate. Complete drying up during the growing season indicates deficient moisture in the soil. Distinction should be made between summer and winter losses, as the latter usually are not attributable to an actual deficit of soil moisture.

If, with adequate soil moisture, active growth does not begin in June, there is reason to believe that the temperature is too low. Plants suffering from deficient heat during the first growing season usually show a gradual decline, persisting into the second or third season.

Another cause of failure may be deficient light or direct solar radiation, as distinguished from low air temperature. Too much shade, even though accompanied by favorable soil moisture and air temperature, results in slender stems and thin pale leaves. In these cases there may be a question as to whether the deficiency is mainly in light or in heat energy.

It is not known whether all the soils concerned are equally favorable to all species. Enough tests have been made to indicate that there is nothing in any of the soils which is distinctly inimical to any species. If adequately watered, blue spruce and Douglas fir grow well when planted in the heavy western yellow pine soil, and greenhouse tests have shown that western yellow pine seedlings thrive in the light soils of the Douglas fir and Engelmann spruce sites. In this study no failures have been attributed directly to unfavorable soil.

A record of survival from 1918 to 1926 and the condition of the living plants eight years after planting are given in Table 31. In drawing conclusions as to the causes of failure or probabilities of success, the survival record has been supplemented by careful observations of the planted trees and also of native trees on the same areas, where the native trees promised to furnish information bearing on the problem.

TABLE 31.—*Survival of plantings made in 1918 and 1919 in different forest types in the San Francisco Mountains*

Forest type and species	Number of trees planted in—			Number of trees surviving in—						Condition in October, 1926
	June, 1918	April, 1918	April, 1919	August, 1918	November, 1918	July, 1919	October, 1920	August, 1924	August, 1926	
Western yellow pine type:										
Western yellow pine	------	10	----------	9	8	8	8	6	----------	Destroyed by fire in 1924.
Douglas fir	------	14	----------	8	8	7	2	0	0	
Blue spruce	------	10	----------	8	6	6	4	1	1	Normal, in shade of western yellow pine; height 2 feet.
Limber pine	------	5	----------	3	2	2	1	0	0	
Bristlecone pine	------	5	----------	5	5	4	1	0	0	
				September, 1919	May, 1920	August, 1920	August, 1921	August, 1924	August, 1926	
Douglas fir (not watered)	------	----------	10	10	10	0	0	0	0	
Douglas fir (watered)	------	----------	20	20	20	14	6	3	2	Tops dead; height 18 inches.
Blue spruce (not watered)	------	----------	10	10	10	2	0	0	0	
Blue spruce (watered)	------	----------	20	20	20	19	18	17	17	All but 4 in good condition; height 3 to 5 feet.
		May, 1918	April, 1919	November, 1918	August, 1920	September, 1921	October, 1923	August, 1924	August, 1926	
Douglas fir type, northwest slope:										
Douglas fir	------	5	----------	5	5	5	4	3	3	Normal; height 12 to 16 inches.
Blue spruce [1]	------	5	----------	5	5	5	5	5	5	Tops dead; height 8 to 11 inches.
Western yellow pine	------	4	----------	4	3	1	0	0	0	
Bristlecone pine	------	1	----------	1	1	1	0	0	0	
Limber pine	------	1	----------	1	1	0	0	0	0	
Douglas fir type, aspen bench:										
Douglas fir	------	4	----------	4	4	4	3	3	3	Normal; height 15 to 20 inches.
Blue spruce	------	6	----------	6	6	5	5	5	5	Normal, thrifty; height 14 to 18 inches.
Western yellow pine	------	4	----------	4	4	3	3	2	2	Very slender; height 12 to 20 inches.
Bristlecone pine	------	2	----------	2	2	2	1	1	1	Normal; height 14 inches.
Limber pine	------	2	----------	2	2	2	1	1	1	Normal; height 13 inches.

[1] Shaded during greater portion of the day.

TABLE 31.—*Survival of plantings made in 1918 and 1919 in different forest types in the San Francisco Mountains*—Continued

Forest type and species	Number of trees planted in—			Number of trees surviving in—						Condition in October, 1926
	June, 1918	June, 1919	November, 1918	August, 1920	November, 1921	July, 1922	October, 1923	July, 1924	August, 1926	
Limber pine - bristlecone pine type:										
Western yellow pine [1]	5		2	2	2		2	2	1	Normal; height 15 inches.
Douglas fir	3		2	0	0		0	0	0	
Blue spruce	5		4	2	1		1	1	1	Poor condition.
Limber pine	3		2	2	1		1	1	1	Normal; height 19 inches.
Bristlecone pine	3		3	2	2		2	2	2	Normal; height 12 to 20 inches.
Western yellow pine		14		9	8		6	6	5	3 normal; height 12 to 15 inches; 2 with top dying.
Engelmann spruce type, ridge:										
Western yellow pine	6		6	5	2	1	1	0	0	
Douglas fir	5		5	4	2	1	1	1	1	Very slender; height 14 inches.
Blue spruce	7		7	4	0	0	0	0	0	
Limber pine	2		2	2	2	2	2	2	2	Normal; height 11 to 14 inches.
Bristlecone pine	1		1	1	1	1	1	0	0	
Western yellow pine		10		6	6	4	3	0	0	
Engelmann spruce type, northwest slope:										
Western yellow pine	3		3	0	0	0	0	0	0	
Douglas fir	3		3	3	3	2	2	2	2	Poor; height 7 to 8 inches.
Blue spruce	9		9	6	3	2	1	0	0	
Limber pine	3		3	3	2	1	1	1	1	Poor; height 4 inches.
Bristlecone pine	2		2	2	2	2	1	1	1	Poor; height 6 inches.
Western yellow pine		6		5	3	2	0	0	0	

[1] All western yellow pine and limber pine defoliated by sheep in summer 1926.

WESTERN YELLOW PINE

This species has been planted successfully in the western yellow pine zone for several years, and the results shown in Table 31 are regarded as fairly typical.

Western yellow pine was planted on two sites in the Douglas fir zone. It failed completely on the northwest slope, which is the more typical Douglas fir site. Two specimens still persist on the aspen site which, according to soil-temperature records, is slightly warmer than the northwest slope. The slender form of these plants suggests too much shade. On the aspen site, herbaceous vegetation consisting largely of vetch contributes to the shade, as do the aspen trees. On the northwest slope, however, there is less herbaceous vegetation, the shade coming mainly from conifers. The plants receive about three hours of full sunlight in the middle of the day. According to other observations, this is scarcely enough for normal development of western yellow pine, particularly where air temperature is near the minimum. It is evident from Table 21 that moisture is not a factor here or in the zones above this, because the soil at all times contains more moisture than is found in the western yellow pine zone. A native western yellow pine about 40 feet tall occurs some 200 yards distant and 50 feet lower than the aspen site, in an open situation on a steep south slope. Another specimen, taller and apparently older, occurs about 100 feet higher, also on a steep south slope. It is surrounded by aspen but probably started in the open. Both trees have borne scanty crops of cones in the past, and no seedlings are in evidence.

On the limber pine-bristlecone pine site a number of western yellow pines have survived. Partial defoliation each spring furnishes evidence of a severe struggle against adverse winter conditions, a combination of high winds, strong insolation, and low temperature. The wind movement here is second only to that at the timber-line station, and evaporation surpasses that at all the stations above the piñon-juniper type. The soil remains frozen scarcely as long as in the western yellow pine type, the temperatures at the depth of 1 foot being actually higher during January and February. Soil moisture is higher throughout the growing season than in the yellow pine zone. Several of these plants give promise of survival. During the summer of 1926, the new foliage of all the western yellow pines and limber pines on this slope was removed by sheep. Wire inclosures have since been erected.

In the Engelmann spruce zone, western yellow pine planted in the opening on the ridge (station 10B) gave promise of success during the first two years but after that failed rapidly. Growth began here each year about a month later than in the western yellow pine zone, and by the middle of August the new shoots were only from 1 to 2 inches long or about one-half the length of those in the western yellow pine zone.

On this same site, nursery beds were sown to western yellow pine, Engelmann spruce, and bristlecone pine in 1918 and 1919. Both the spruce and bristlecone pine came up so thickly that thinning was necessary; in 1924 the seedlings were from 9 to 12 inches high and were again contending for space. The western yellow pine seeds, which had tested between 60 and 70 per cent, germinated only 5 per cent in 1918 and 11 per cent in 1919. On May 26, 1924, there were 23 seedlings from about 1,000 seeds sown. They were then, at the age of 4 or 5 years, only 5 or 6 inches tall, although seedlings of the same age in the yellow pine nursery were more than a foot tall. In September, 1927, only 4 of these seedlings were living. They were from 8 to 11 inches tall, very slender, and had short, thin leaves. Bristlecone pine and Engelmann spruce in the same bed were from 11 to 13 inches tall and of good form. In August, 1928, 3 of the western yellow pines were still alive but continued subnormal in development, whereas the bristlecone pine and spruce were in excellent condition.

The behavior of western yellow pine on the northwest slope of the Engelmann spruce zone (station 10A) was exceedingly interesting. The site is in an opening receiving direct sunlight about three hours in the middle of the day in summer. The ground cover is sparse. On July 31, 1918, six weeks after planting, all species except western yellow pine were recorded as growing. On September 9, the buds of western yellow pine had opened, but the new leaves were barely visible. The usual rapid elongation characteristic of this species did not take place. During the next summer a few of the plants grew as much as an inch, but in no case did the needles attain more than half normal length. A year later every plant was dead. Six other yellow pines set out in 1919 reacted as did those of the 1918 planting. Direct seeding with western yellow pine gave equally decisive results. Out of the 200 seeds sown in a screened bed in 1918 only 1 germinated. The following year 6 more came up, and a year later all were dead.

These tests indicate that western yellow pine might be planted successfully in the Douglas fir zone if placed in open situations and on southerly exposures but that it will not succeed on typical Douglas fir or Engelmann spruce sites. Shortness of the growing season and deficient heat during this season are thought to be the chief reasons for failure. The mean maximum air temperature during the period May to September falls from 72.2° F. in the western yellow pine zone to 64.7° in the Douglas fir zone, and the corresponding decline in physiological temperature efficiency is from 3,821 to 2,008. (Table 11.) From the western yellow pine zone (25 per cent shade) to the uppermost natural occurrence of the species, the summer soil temperature at a depth of 1 foot drops 2.7° (Table 12), and the Douglas fir zone shows a further decline of 4.8°. That winter temperatures are not vitally important is indicated by the fact that relatively few losses have occurred during the winter, except on the limber pine-bristlecone pine site where wind dominates the environment. Even on the northwest slope of the Engelmann spruce zone where the soil remains frozen for five months, the planted western yellow pines showed no signs of winterkilling, probably because of the heavy snow blanket.

DOUGLAS FIR

Where not watered, Douglas fir has failed completely in the western yellow pine zone. The soil moisture and high evaporation here as compared with those in the Douglas fir zone and the fact that nearly all the plants died during the dry summer of 1920 point to drought as the critical factor. The ultimate failure of most of the plants which were irrigated is attributed partly to the fact that the irrigations probably were not frequent enough but mainly to frosts, which have killed back the new growth each spring. If the new shoots are completely killed every year, it is evident that the plant must eventually succumb as the old foliage is shed. If there were enough moisture for Douglas fir in the western yellow pine zone, spring frosts would still in many places prove a limiting factor.

In the Douglas fir zone the planted trees promise to succeed on both sites. In addition to the experimental planting here recorded, several acres have been successfully planted under aspen on near-by sites. The oldest of these plantations was made in 1911. The trees are from 3 to 6 feet tall, somewhat below normal because of damage done by browsing sheep.

As might well be expected, Douglas fir was eliminated from the limber pine-bristlecone pine site during the first year. Wind and high insolation are thought to be the most adverse factors.

Both the northwest slope and the ridge in the Engelmann spruce zone appear to be inhospitable to Douglas fir. Although three plants are still living, they are clearly abnormal. The wide divergence between the northwest spruce slope and the Douglas fir sites in both air and soil temperatures seems to be a decisive factor. Perhaps the most significant difference is in the physiological temperature efficiency, which is 2,008 in the Douglas fir zone and only 994 in the Engelmann spruce. The ridge site of the Engelmann spruce zone is somewhat warmer than the northwest slope (Table 6) but is still much colder than the Douglas fir zone. The advantage of low evaporation is on the side of the spruce sites.

BLUE SPRUCE

Blue spruce, which normally grows under much the same conditions as Douglas fir, has shown itself more resistant to drought, high insolation, and frost than that species. In the western yellow pine zone all the unwatered trees, though showing considerable persistence, died, except one which was planted on the north side of a bushy yellow pine sapling about 8 feet tall, which shaded the seedling during the hottest part of the day. (Fig. 37.) Experiments with western yellow pine in 1919 showed that shading approximately equivalent to that received by this spruce cut down the transpiration by 32 per cent. In August, 1927, this plant was 30 inches tall and of normal appearance. Plants which were irrigated at intervals of about two weeks during the driest seasons nearly all survived, and the tallest were more than 7 feet high in 1927. The relation between watered, unwatered, and shaded plants indicates clearly that moisture is the dominant factor. Blue spruce may live in the shade of trees or buildings in the western yellow pine zone, but to grow at a normal rate it must have more moisture than is usually provided here by precipitation.

On the northwest slope of the Douglas fir zone, the blue spruce were planted along the south edge of the opening where they were shaded the greater part of the day. Though still living in 1926, they were not thrifty and had grown less than the shaded spruce in the

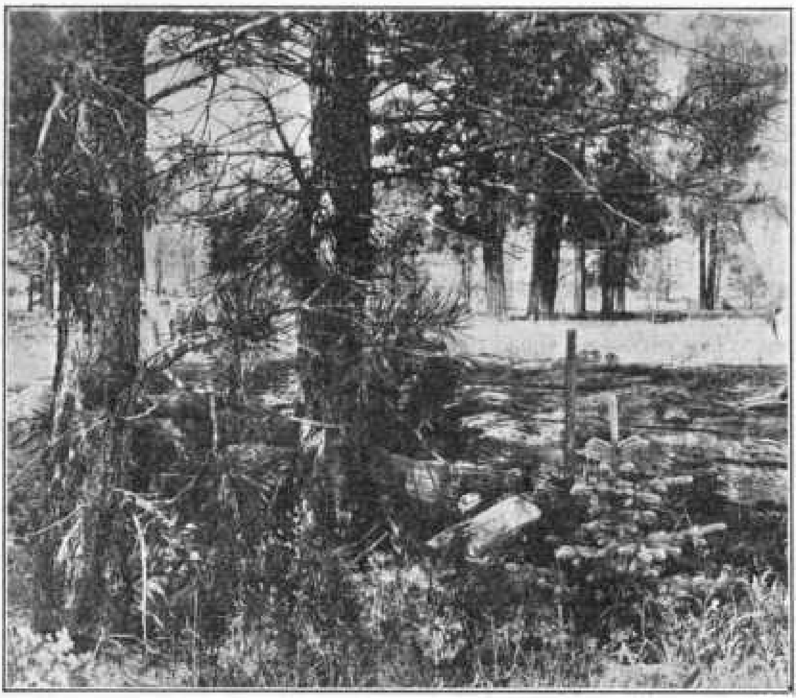

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FIGURE 37.—Blue spruce planted in the shade of a pine sapling. All plants of this species, as well as of Douglas fir, limber pine, and bristlecone pine, planted in the western yellow pine zoue, died where not watered or shaded. This specimen of blue spruce, shaded but not watered, was 26 inches tall nine years after planting; others exposed to full sun but watered were from 5 to 7 feet tall

FIGURE 38.—Blue spruce planted under aspen in the Douglas fir zone. Western yellow pine has failed on this site, probably on account of the shade cast by the aspen and the luxuriant herbaceous vegetation. Soil moisture is abundant in all seasons

western yellow pine zone. On the aspen site (fig. 38), where shade is less and soil temperature a little higher, they are thriving but are much smaller than plants which have been watered in the western yellow pine zone. Although blue spruce occurs fairly generally in the Douglas fir zone and in the lower part of the Engelmann spruce zone, its behavior indicates a preference for relatively warm situations with abundant moisture. For reasons not understood, it does not occur naturally in the San Francisco Mountains.

LIMBER PINE AND BRISTLECONE PINE

Limber pine and bristlecone pine are very similar in their habits; both seem to prefer rather open situations, and both are able to grow

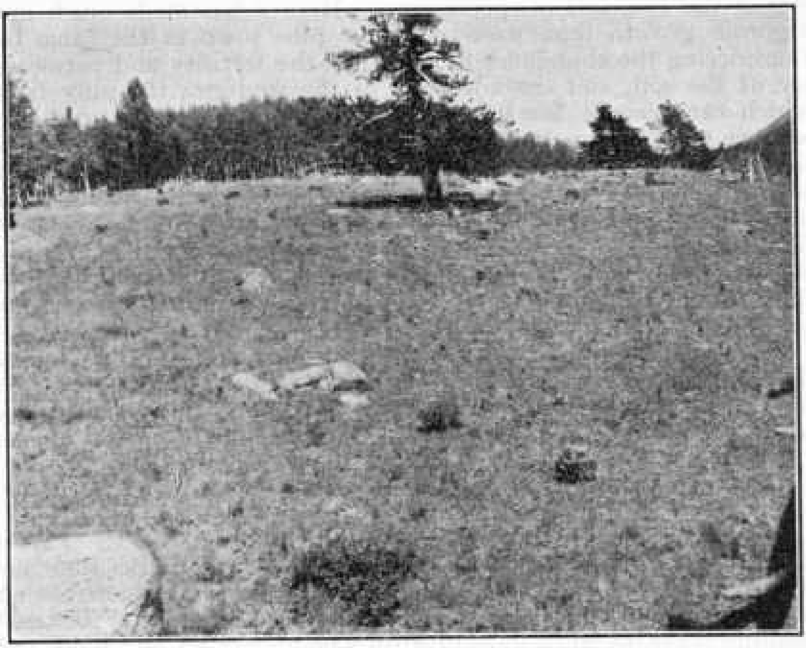

FIGURE 39.—Planting site in the limber pine-bristlecone pine zone (steep southwest slope at 10,000 feet elevation). High wind, accompanied by strong insolation, is the critical factor here. Limber pine and bristlecone pine have succeeded; western yellow pine is uncertain; Douglas fir and blue spruce failed

on wind-swept slopes and ridges where other trees fail. (Fig. 39.) Bristlecone pine in the San Francisco Mountains ranges distinctly higher than limber pine. In the western yellow pine zone both species made a promising start, but the summer of 1920 apparently was too dry for them. In the Douglas fir zone, where limber pine grows naturally, both failed on the northwest slope, but since each species was represented by only one plant the test is not conclusive. On the aspen site in 1927, both were growing well, and on the limber pine-bristlecone pine site they were the only species, with the possible exception of western yellow pine, whose success seemed assured. Both were failing on the northwest slope of the Engelmann spruce zone, and this accords with the fact that neither occurs

47388°—31——8

naturally on sites as cold as this. On the ridge site, which is but slightly above its natural range, limber pine gives promise of becoming established. The death of the solitary bristlecone pine planted here is not significant, being probably due to aftereffects of trampling by horses which were put inside the inclosure by campers. Seedlings raised in a nursery bed are, according to all indications, at home here, as they should be since the species occurs naturally both above and below this site.

ENGELMANN SPRUCE

As has already been explained, Engelmann spruce was not included in the planting experiment but was grown from seed on the ridge site of the Engelmann spruce zone. Here it has made much more vigorous growth than western yellow pine sown in the same bed. Considering the abundance of moisture, the fertility and permeability of the soil, and the adequacy of the sunlight, the only factor which can account for the superiority of Engelmann spruce over western yellow pine on this site is the ability of the spruce to function at low temperatures. On the aspen bench of the Douglas fir planting site Engelmann spruce does not occur naturally, but on the northeast slope it is found in the immature stage in the shelter of larger trees. In a few moist situations it grows on the same site as western yellow pine, but ordinarily there is a gap between the lower limit of the Engelmann spruce and the upper limit of western yellow pine.

Engelmann spruce seed sown in 1918 on the northwest slope of the Engelmann spruce zone germinated, but the seedlings died in the course of one or two years. Their behavior, along with that of natural seedlings discussed elsewhere, is attributed to deficient heat.

NATURAL OCCURRENCE AN INDICATION OF REQUIREMENTS

It may be concluded from these experiments that the natural occurrence of all species in this region very nearly marks their possible range. The theory that the barriers imposed by moisture and temperature can be removed by assisting the tree through the early seedling stage, as when nursery-grown plants are set out, holds only within narrow limits. Where, for instance, western yellow pine is widely scattered on a south slope at high elevation, it is probable that the numbers can be increased by planting if all shade is removed; but it would be unwise to attempt to go above the last natural specimens. Moreover, a stand established under such conditions would not maintain itself by natural reproduction because the seedlings could not bear the reduction of heat which even partial shading by larger trees would bring about. Similarly, although the lower range might be extended slightly by planting, it is doubtful whether a stand established by this means on sites too dry for natural reproduction would survive the exceptional droughts which come periodically.

The suggestion that species are kept within restricted zones by competition is also of limited application. No doubt western yellow pine is driven from optimum Douglas fir sites, and Douglas fir is in turn driven from optimum Engelmann spruce sites by competitors which are better adapted to photosynthesis in low air temperature and low insolation. But in many openings in both the Douglas fir and Engelmann spruce zones western yellow pine or Douglas fir would temporarily meet no interference. They extend their upper range in places by taking possession of openings, but each soon reaches a limit beyond which it apparently can not go, regardless of competition. When a shade-enduring species pushes downward below its normal range, it is favored rather than retarded by the presence of other species. Thus, Douglas fir, white fir, and limber pine reproduce in the shade of western yellow pine on sites where they could not become established without shelter. It is seldom, however, that they can descend below the upper half of the western yellow pine zone, except on steep north slopes or along watercourses, because soil moisture becomes deficient. Scattered seedlings of white fir, Douglas fir, and limber pine are found under western yellow pine or

FIGURE 40.—Planting site in the Engelmann spruce zone, natural opening, northwest slope, elevation 10,500 feet. All species failed here. Natural seedlings of Engelmann spruce have started several times, only to die in the second or third years

on the north side of rocks or logs on level mesas as much as a thousand feet below their usual range. The fact that on such sites none of these species are found beyond the sapling stage is considered good evidence that they can not assume a place in the upper crown canopy.

TEMPERATURE AND MOISTURE AS LIMITING FACTORS IN NATURAL DISTRIBUTION

In a preliminary report by the writer (*34*) this subject of the factors limiting natural distribution was discussed in considerable detail, and the conclusion was reached that the upper altitudinal limits of each species in this region are determined by low temperature, whereas the lower limits are determined by deficient moisture, be it low precipitation, excessive evaporation, or unfavorable soil conditions. Subsequent investigations and observations support this conclusion. Anyone may test it for himself merely by observing the conditions under which the various species are found when they occur outside of their usual habitats. Scattered individuals appear in places 1,000 or more feet above or below the zone which the species normally inhabits. Downward extensions are always on northerly aspects, along watercourses, or on other relatively moist sites. Upward extensions, on the other hand, follow ridges or south-facing slopes which receive maximum insolation.

In this manner western yellow pine, which normally occupies altitudes between 7,000 and 8,000 feet in the region about Flagstaff, follows Oak Creek down to an altitude of 4,000 feet and ascends open south slopes on the San Francisco Mountains to 9,300 feet. It has been successfully transplanted under irrigation near Phoenix at an altitude of 1,100 feet. Arizona cypress, whose usual habitat is between 6,000 and 7,000 feet, thrives under irrigation in the hottest valleys of southern Arizona. Douglas fir, probably most sensitive to high insolation of all the species in the region, descends 3,000 feet below its normal range in Oak Creek Canyon. Unlike western yellow pine, however, Douglas fir does not go far above its normal range, probably on account of its inability to withstand high winds and evaporation on open south exposures. White fir and blue spruce, common associates of Douglas fir at altitudes between 8,000 and 9,000 feet, are rather common ornamentals in Albuquerque and other places below an elevation of 5,000 feet. Engelmann spruce is usually at its best at elevations ranging between 10,000 and 11,000 feet, but in many places in moist, sheltered canyon bottoms and on steep north hillsides it goes well below 9,000 feet. With artificial watering it grows well in Flagstaff at 7,000 feet. In the San Francisco Mountains it reaches the highest altitude attained by any tree.

According to the writer's observation, the species which normally occupy high altitudes are unable to grow in low altitudes because of the drought rather than the high temperature prevailing there; they are found at high elevations not because they require low temperature but because they must go where they can find sufficient moisture. Likewise, species which occupy relatively low altitudes are there not because they demand dry soil and dry air but because they must have relatively high temperature and are able to withstand the dry conditions accompanying it. They would respond with greatly increased growth to the copious rainfall of the higher levels, but the temperature accompanying this rainfall is too low for them.

HIGH TEMPERATURE

Bates, (*1*, *2*), as a result of his investigations in Colorado, regards low temperature as the primary limiting factor in the upper ranges but, differing with the writer, believes that high temperature rather than drought is the condition which keeps the high-altitude trees, such as Engelmann spruce and the firs, out of the lower climatic zones. In other words, he regards temperature as the controlling factor both above and below. He attributes the adverse condition not so much to high air temperature in itself as to local heating of the foliage and, in the case of seedlings, to heating of the stem at the ground line. Toumey and Neethling (*44*) and Hartley (*19*) also have called attention to the injury of conifer seedlings by high surface-soil temperatures, which cause lesions to appear in the stem when the temperature rises above 122° F.

When dealing with leaf injury, it is difficult to make a hard and fast distinction between the effects of heat and drought. High temperature increases evaporation from the soil and also the rate of transpiration. An abundant supply of soil moisture, within the limits of the capacity of the roots to absorb it, enables the plant to withstand a high rate of transpiration without ill effects. When a plant dies during a period of hot, dry weather, it is difficult to say whether heat or drought was the direct cause. But if death can be averted by applying water to the soil it seems logical, in the absence of proof to the contrary, to attribute the trouble to drought.

If lesions or similar injuries appear in the stem when the roots are in contact with moist soil, it seems fair to regard heat as the primary cause. In the Southwest, bare soils fully exposed to the sun not infrequently attain temperatures of 140° F. or more at the surface. This probably explains why, as pointed out by the writer (*34*), survival of western yellow pine seedlings is usually better on spots having a light cover of litter or herbaceous vegetation than on those wholly devoid of cover. Thickness and character of bark more, perhaps, than any other quality determine the ability of a plant to resist heat injury. The "sun scald" common in poplars and other thin-barked trees is not essentially different from the heat lesions described by Bates and Roeser (*3*), Toumey and Neethling (*44*), and Hartley (*19*). In Arizona, conifers beyond the early stage are practically immune unless the soil becomes unusually dry. In nursery practice, western yellow pine has been observed to suffer rather more than the firs and spruces. This may be because pine beds are usually allowed to become drier than fir and spruce beds. A more common trouble in Douglas fir when exposed to the sun, both in the nursery and in plantations, is a drying of the young shoots. Blue spruce and Norway spruce are affected similarly but in less degree, since tender shoots and leaves, though often wilting temporarily, seldom die if the soil is moist. (Fig. 41.) These symptoms are thought to indicate deficient water replacement rather than direct heat injury, because they are alleviated, if not entirely prevented, by copious watering.

While conceding that young seedlings are often killed by high temperatures at the surface of the soil, the writer does not regard this or any other form of heat injury as a common limiting factor in the downward extension of the natural range of forest trees. If high surface temperatures were a limiting factor in the presence of adequate soil moisture, seedlings would overcome it by taking advantage of the shelter offered by logs, stones, shrubs, trees, and other objects which cast a shadow over small areas. Even on the desert, where air temperatures rise to 115° F., there are shaded spots where the surface soil does not become appreciably hotter than the air. It is, however, safe to say that no one has seen spruce, fir, or even pine seedlings springing up under creosote bushes.

LOW TEMPERATURE

Low temperature appears to become a barrier mainly when it involves a deficiency of heat energy during the growing season. This deficiency is usually less apparent in the mean air temperature than in the mean maximum, the duration of high temperatures, or the physiological index of temperature efficiency. (Table 11.) Western yellow pine at the upper limits of its range is poor in both seed production and germination. Observations of other species confirm a similar conclusion as to seed production, but no information on germination is available. Seedlings are less able to function on cold sites than are older trees, because in the seedling stage direct solar radiation is more likely to be intercepted by neighboring trees, herbs, shrubs, logs, rocks, and other objects than it is after the young trees are several feet high. If interference of this sort can be avoided, as when seedlings chance to gain a foothold in temporary openings, a species may live to great age in a temperature zone from which it would otherwise be barred. This is clearly the case with western yellow pine at its extreme upper limits.

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FIGURE 41.—Blue spruce with wilted leader, evidently due to inability of roots to supply water as fast as it is transpired. Norway spruce and Douglas fir planted in the western yellow pine zone behave in the same manner. If the soil is well watered the terminals may wilt in the hot sun but regain their turgidity at night. If the soil is dry, not only the leader, but also the upper shoots, dry up

Reference has already been made to two forms of winterkilling, one attributed to the direct effect of low temperature of long duration and the other to the physiological dryness of frozen soil. It is probable that both these factors may affect the distribution of forest trees in this region under certain conditions, but they are not thought to be of widespread importance as limiting factors. Within the writer's observation, only the woodland species have shown indications of injury from persistent low temperatures. Western yellow pine suffers from what appears to be physiological drought in its middle and lower but rarely in its upper range. In the San Francisco Mountains little winterkilling of any kind occurs above the western yellow pine zone, except on sites exposed to strong winter winds.

As pointed out in the preliminary report on this study (*34*), timber line on well-insolated ridges apparently is due to high winter winds rather than low temperatures. This opinion is based upon the fact that beyond the upper line of tree growth the spruce continues several hundred feet up the slope in a bushy or prostrate form. The height of these subnormal specimens corresponds to the depth of the snow blanket, and the tips which extend above the snow line are usually stripped of leaves and often bark as well. This extreme condition is attributed more to the mechanical action of the wind than to its drying effect, but this also is evident. True low-temperature timber lines occur on northerly aspects where the spruce ceases abruptly without a transitional bushy or prostrate form and without evidence of winterkilling. Although summer air temperatures here are not appreciably below those on the ridges (Table 6) the insolation and total available heat energy must be less.

On wind-swept burns of northerly aspect in the optimum spruce belt, typical winterkilling occurs in Engelmann spruce, corkbark fir, and bristlecone pine. The trees here consist of scattered saplings, few of which exceed 10 feet in height. Each spring a large proportion of the foliage is brown above snow line on the windward side. Although the reestablishment of the forest is being severely retarded, it is not being prohibited.

The fact that winterkilling is rare in the Engelmann spruce and Douglas fir zones, notwithstanding that the soil remains frozen from three to five months, may give rise to the impression that the species occupying these zones are extremely drought resistant. In the light of the account given in the foregoing paragraph, these species are not immune to winterkilling when exposed to drying conditions in association with frozen soil. Their immunity in stands on well-protected or average sites may be attributed to the absence of high evaporation stresses. Another factor which probably is of considerable importance is that in the higher altitudes the leaves and stems remain covered with snow and ice for several days after each storm, and thus a considerable quantity of this moisture may enter the living tissues.

RANGE OF TEMPERATURE AND MOISTURE WITHIN EACH FOREST ZONE IN THE SOUTHWEST

If, as was concluded in the foregoing pages, temperature and moisture determine the altitudinal range of species, it is desirable to analyze the climate and soil data presented on earlier pages to ascertain where the temperature and moisture limits for each species lie. Before proceeding to a study of the requirements of individual species, however, the range of temperature and moisture conditions in each forest zone will be fixed as definitely as deficient data and complex physical relationships permit. In the following summaries, the extremes of each range are averaged for several years, representing individual stations or groups of stations near the upper and lower limits of each zone in different localities. Summer temperature is regarded as a better index of heat conditions than annual temperature, but the most reliable index of precipitation is considered to be the total for the year, as trees make their growth on moisture stored during the preceding winter as well as on that which falls during the growing season.

For reasons which have been discussed elsewhere in this bulletin, the mean air temperature is not regarded as a good index. It is presented, however, for purposes of comparison in other regions because often this is the only figure given in published temperature records. The mean maximum is considered more indicative of effective temperature, and of still greater significance are the summations showing duration of various temperatures, the product of intensity by duration, and the physiological temperature efficiency, as given in Table 11. Unfortunately, these summations can be used to only a slight extent, because the only series of mountain stations for which they are available is the one in the San Francisco Mountains. In order to bring out more effectively the relation between various types, as was previously explained, temperature summations have been made for the five months (May to September, inclusive), instead of the four months (June to September) employed in computing means of current temperature.

In the following paragraphs the physical conditions as found in each forest zone are summarized. These figures are derived from the various tables appearing in this bulletin but have been modified in a few cases where data at the extremes of a type are lacking or are known to be abnormal. As previously explained, records of air temperature and precipitation have been obtained from many stations throughout Arizona and New Mexico, but temperature summations, soil temperature, soil moisture, and evaporation records are available for only one or a few stations in each forest zone of the San Francisco Mountains during periods of one to three years.

Woodland zone.—Summer temperatures (June–September): Mean 65° to 69° F., mean maximum 79° to 85°, mean soil at 1 foot 64° to 75°, physiological efficiency (total, May–September) 8,412. Moisture: Annual precipitation 12 to 20 inches, evaporation (total, June–September) 30 to 40 inches, available soil moisture at 1 foot (average, May–September, 1918) 2.6 per cent, lowest (September, 1918) −0.4 per cent.

Western yellow pine zone.—Summer temperature (June–September): Mean 59° to 63° F., mean maximum 74° to 80°, soil at 1 foot 56° to 65°, physiological efficiency (total, May–September) 3,822. Moisture: Annual precipitation 18 to 25 inches, evaporation (total, June–September) 18 to 26 inches, available soil moisture at 1 foot (average, May-September, 1918) 3.8 per cent, lowest (September, 1918) –0.5 per cent.

Douglas fir zone.—Summer temperature (June–September): Mean 56° to 58° F., mean maximum 67° to 74°, soil at 1 foot 52° to 54°, physiological efficiency (total, May–September) 2,008. Moisture: Annual precipitation 22 to 34 inches, evaporation (total, June–September) 12 to 16 inches, available soil moisture at 1 foot (average, May–September, 1918) 13.7 per cent, lowest (August, 1918) 7.6 per cent.

Engelmann spruce zone.—Summer temperature (June–September): Mean 50° to 56° F., mean maximum 58° to 68°, soil at 1 foot 44° to 50°, physiological efficiency (total, May–September) 994. Moisture: Annual precipitation 27 to 36 inches, evaporation (total June–September) 10 to 13 inches, available soil moisture at 1 foot (average, May–September, 1918) 13.7 per cent, lowest (September, 1918) 3.8 per cent.

COMPARISON WITH COLORADO CONDITIONS

It is of interest to compare some of the foregoing data with those obtained by Bates (*2*) in Colorado. The most comparable and significant data presented by Bates are in the mean air temperatures for the growing season, which he considers as extending from June 1 to September 10 instead of from June 1 to September 30, the period used in the present investigation. Hence, the average should be slightly higher in Bates's experiments. The ranges of mean temperature for the growing season in Colorado are as follows: Western yellow pine zone, 54° to 64° F.; Douglas fir zone, 54° to 58°; and Engelmann spruce zone, 49° to 56°. In Arizona and New Mexico the corresponding figures for a slightly longer period are 59° to 63°, 56° to 58°, and 50° to 56°. The following are the average of growing-season means at several stations in Colorado: Western yellow pine zone, 59.2°; Douglas fir zone, 56°; and Engelmann spruce zone, 51.6°. Corresponding averages in Arizona and New Mexico are 60.9°, 57°, and 53.8°. The approximate range of summer soil temperature at a depth of 1 foot in the three zones, in the order given above, is, for Colorado, 55° to 60°, 44° to 53°, 40° to 50°; and for Arizona, 56° to 65°, 52° to 54°, and 43° to 53°.

Both air and soil temperatures are consistently lower for corresponding forest zones in Colorado, although the agreement on the whole is as close as can be expected. One might expect to find the same trees occupying cooler sites in Colorado because the precipitation is less than in Arizona and New Mexico. The western yellow pine zone apparently receives nearly the same precipitation in Colorado as in the States to the south, but the Douglas fir and Engelmann spruce zones receive only from 21 to 28 inches, whereas in Arizona and New Mexico they receive from 22 to 36 inches, the average being 26 inches for the Douglas fir and 34 for the Engelmann spruce. There appears to be but little consistent increase in precipitation with altitude above the western yellow pine zone in Colorado. If the firs and spruces require more moisture than western yellow pine, this would force them to seek colder climates where evaporation, transpiration, and probably growth would be less than where higher temperatures prevail.

Another matter deserving consideration is that in widely separated regions different strains of the same species may be involved. It is well known that western yellow pine of the central and southern Rocky Mountains differs markedly in requirements and growth habits from the form of the same tree occurring on the Pacific coast and northern Rocky Mountains. Moreover, differences have been noted between the western yellow pine of Arizona and that of northern New Mexico and Colorado. In northern New Mexico, blue spruce and Engelmann spruce merge into one another so closely that it is often difficult to distinguish one from the other. The same is true of limber pine and Mexican white pine (*Pinus strobiformis*) in certain sections of Arizona and New Mexico. In fact, what is called limber pine in these two States appears to be a different tree from the limber pine of Colorado. Other species present similar problems. Granting that we are dealing with climatic adaptations only, this fact in itself would account for a wide range in the requirements of a species.

INTERDEPENDENCE OF LIMITING FACTORS

As has been repeatedly pointed out in this bulletin, the lines of demarcation in the characteristics of forest types and in physical requirements of species can not be drawn with precision. This is particularly true where indirect rather than direct physical factors are involved. The amount of precipitation, for instance, is at best only a rough measure and may be entirely misleading as to the amount of moisture available, because the proportion of the precipitation which is placed at the disposal of the plants varies greatly with topography and soil. Moreover, the effectiveness of the actually available moisture stored in the soil depends upon a number of other factors such as temperature, evaporation, and soil characteristics. A good illustration of the interdependence of factors is furnished by the Natural Bridge station in Arizona. A record of 30 years shows an average annual precipitation of 23.65 inches, which is slightly above that of typical stations in the western yellow pine zone. Yet western yellow pine occurs sparingly here and is of subnormal growth. The vegetation is more characteristic of the woodland zone. A clue to the cause of this condition is found in the high temperatures which, though not directly injurious, induce a high rate of evaporation. Records, if available, would undoubtedly show evaporation to be so high as to render the precipitation inadequate for western yellow pine. The opposite extreme obtains in the vicinity of Tres Piedras and Elizabethtown, N. Mex., where western yellow pine grows with 2 or 3 inches less than the usual minimum precipitation. In these two localities, the altitude is about 8,500 feet, and the temperature during the growing season is from 2° to 3° F. below the average for western yellow pine. Apparently similar relations occur rather generally in Colorado, where Douglas fir and Engelmann spruce in particular seem to grow with considerably less moisture than in Arizona and New Mexico.

LIMITS OF TEMPERATURE LESS VARIABLE THAN THOSE OF MOISTURE

Temperature as a limiting factor is far more definite than is precipitation. True, this greater definiteness may be partly more apparent than real, since temperature measurements are probably a more accurate expression of heat conditions than precipitation measurements are of moisture conditions. But there is also good reason to consider temperature requirements more fixed because temperature fluctuates less from year to year than does precipitation.

Low temperature appears to be a more rigid barrier than drought. A plant near the lower limits of its range may become established during a series of wet years and when dry years come it may be able to survive at the expense of slow growth until better conditions return. Thus it may succeed in holding on through many years in a zone in which the moisture supply is below the normal minimum for the species. The woodland species, especially, show great capacity for adjusting themselves to drought and thus to a degree surmounting this barrier. The evergreen oaks may still persist on the drier sites as mere shrubs, whereas on adjoining bottom lands they grow to be good-sized trees. Along the lower edges of the woodland, junipers push out into the drier grassland, gradually decreasing in size until they are not more than a foot or two in height. Western yellow pine exhibits a similar though less extreme dwarfing where it encroaches upon the woodland. Excellent examples of these transitions may be seen along the highway between 15 and 30 miles east of Flagstaff.

If heat instead of moisture is deficient, there appears to be no adequate adjustment. Low temperature results in fewer, smaller, and presumably less active leaves. The processes of nutrition are slowed down until the plant not only can not grow but actually starves to death.

LIMITING FACTOR MINIMA RATHER THAN MAXIMA

Although temperature and precipitation have a more or less definite range in each forest zone, only the lower extremes of the range are regarded as actual limitations. The highest precipitation recorded anywhere in the Southwest is probably not excessive for any tree species common there. Perhaps it would be too sweeping to say that the same is true with regard to temperature, but it is reasonable to believe that all trees would grow better in higher temperatures than prevail in their natural habitats, if these temperatures were accompanied by sufficient rainfall. As it is, the zone of the highest precipitation coincides with that of the lowest temperature and the zone of highest temperature with that of lowest precipitation. In both cases it is the minimum which constitutes the limiting factor.

SPECIFIC REQUIREMENTS OF SPECIES

TEMPERATURE AND MOISTURE REQUIREMENTS

In preceding pages, the main forest types of the Southwest have been depicted in terms of available data on temperature and moisture conditions. The application of these data will now be carried a step further in an attempt to indicate the minimum conditions of temperature and moisture under which each species occurs naturally. In a general way the requirements of a species correspond to those of the forest type in which it occurs, but the two do not always coincide. An endeavor will be made to draw the lines of the species more sharply than type lines, in an effort to indicate conditions under which one may expect normal development rather than bare existence. The difficulty here is the same as in discussing forest types, namely, that temperature and precipitation records are not always a reliable index of heat and moisture conditions. For this reason the study of requirements of species will be based largely on conditions in the San Francisco Mountains and vicinity, where the environment of each climatological station is well known and the conventional temperature and precipitation records are supplemented by data on related factors.

Table 32 gives the minimum limits of temperature and precipitation, as determined in this study, for the principal forest trees in Arizona and New Mexico. If any instance be noted in which the actual minima are higher or lower than those given in the table, it is likely that the surrounding conditions are not common to this region. The modifying influence of temperature and wind upon moisture and the influence of slope, aspect, and soil upon both heat and moisture have been taken into account, but not sufficiently to cover extreme cases. Where a species is found growing with less precipitation than the minimum here indicated the soil is probably unusually favorable to the absorption and retention of water, or low temperatures and light winds favor low evaporation. Similarly, where the given minimum proves inadequate, associated conditions of soil, temperature, and evaporation may be causing waste or high consumption of water. Available soil moisture supplemented by evaporation would undoubtedly provide a better index than precipitation, but records have not been obtained under sufficiently varied conditions to indicate the minima for species. The same difficulty prevents the use of the various temperature summations, any one of which would be better than averages of mean or maximum intensity as usually recorded.

TABLE 32.—*Minimum temperature and moisture conditions under which various tree species usually grow in northern Arizona*

Species	Temperature, June–September			Precipitation		Available soil moisture at 1 foot, May–September
	Mean air	Mean maximum air	Soil at 1 foot	Annual	May–September	
	°F.	*°F.*	*°F.*	*Inches*	*Inches*	*Per cent*
One-seed juniper	65	81	68	12	6	2
Utah juniper	63	79	66	14	7	2.5
Piñon	63	79	66	12	7	2
Alligator juniper	61	78	65	15	8	2.5
Smooth cypress	62	78	67	16	8	3
Western yellow pine	58	70	56	20	9	3.5
Douglas fir	55	62	51	26	12	8
White fir	54	61	50	26	12	8
Blue spruce	53	60	50	24	13	8
Limber pine	54	61	52	24	11	5
Bristlecone pine	52	60	50	28	14	6
Corkbark fir	50	58	46	30	16	8
Engelmann spruce	49	57	45	30	16	8

Optimum conditions of both temperature and precipitation are usually much higher than the lower limits here indicated. Under natural conditions in this region, these optima rarely, if ever, coincide. On the contrary the rule is that approach toward the optimum of one factor leads toward the minimum of the other. High precipitation occurs only at high altitudes where the temperature is too low for rapid growth of most species; the most effective temperatures obtain at middle or low altitudes where the precipitation is too low for rapid growth of most species; the most effective temperatures obtain at middle or low altitudes where the precipitation is too low for rapid growth or even for bare existence. If the lower altitudes provided adequate moisture, with present temperature conditions, the zone of optimum development for each species would probably move downward some 2,000 feet. Such modifications are brought about under artificial conditions where the rainfall in relatively warm zones is supplemented by irrigation.

SOIL REQUIREMENTS

As already stated, the soil variations which affect the distribution of trees in this region are more likely to be physical than chemical. In only a very few instances is there a suggestion of chemical constituents antagonistic to tree growth. One is at the extreme lower limit of tree growth where there may be an accumulation of calcium salts from 1 to 2 feet below the surface, marking the lowest level to which moisture commonly penetrates. In certain areas, rare above the woodland zone, there may be an accumulation of alkali caused by poor drainage. The western yellow pine parks are suggestive of such accumulations, but soil analyses do not confirm their presence. On the contrary, all experimental evidence obtained indicates rather that physical conditions, such as an excess of clay or the presence of hardpan, together with adverse climatic factors, are responsible for these areas.

It may be stated that as a rule conifers in the Southwest reproduce with difficulty in depressions, if the soil is of fine texture. When these sites become adequately stocked, however, they produce the heaviest stands both in point of size of individual trees and in number per acre. Where the soil is very sandy and precipitation light, the rule is reversed as far as reproduction is concerned. Here we find both the best reproduction and the heaviest timber in the valleys. The old silvicultural rule that the densest stocking occurs on poor sites holds in this region for young stands but not for mature and overmature stands. In the western yellow pine zone, particularly, the trees die in patches with the approach of maturity, probably because of deficient moisture in drought periods.

Too little is known about the soil to venture any definite statements regarding soil requirements of species. Existing information indicates that soil limitations which apply under one set of climatic conditions may not apply under another. Observations in the San Francisco Mountains, for example, might lead to the conclusion that spruce and fir grow only on very light soils. In the Wasatch Mountains in Utah, however, these species grow on clay soils. According to Bates (*2*) the soils of the western yellow pine zone in Colorado are everywhere more sandy than those of the Douglas fir and Engelmann spruce zones. In Arizona and New Mexico this relation is reversed in many places.

APPLICATION OF DATA ON FOREST TYPES TO FORESTRY PRACTICE

NEED FOR FURTHER STUDY

The value of definite knowledge as to what conditions different species of forest trees require and in what measure these requirements are met by the various climates and soils in the forest is self-evident. No one will question the theoretical value of such information, but to many it is not clear how it can be applied under the conditions encountered in forestry practice.

One of the first questions to arise is whether the requirements of forest trees can be determined with sufficient accuracy to be of practical value. Doubts about this point are to be expected when one bears in mind the many possible combinations of soil and climate and the inadequacy of present methods of measuring those aspects of the common physical factors which most directly affect plant growth. For example, air temperature is only an indication of heat conditions as they affect the plant, and precipitation is a still cruder expression of moisture conditions. Notwithstanding these limitations, however, such data as are now available promise to be of much value. Further investigations will undoubtedly result in refinements and may establish new and better criteria for measuring plant requirements. If future efforts are directed along the line of exact experimentation supplemented by systematic observations, always aiming to supplant personal opinion by quantitative measurement, the accomplishments of three or four decades are likely to exceed any estimates that can be made at the present time. In pursuing such a course of experimentation and observation the example set by specialized branches of agriculture where, after centuries of empiricism, real progress has come only with the introduction of experimental methods, is being followed.

MEASUREMENT OF SITE FACTORS

In order to make use of specific data on the requirements of species it is necessary to have equally specific data on sites. If this means long-time instrumental records on each site, the obstacles arising are likely to render the entire scheme impractical. Records over long periods, however, are needed only on typical sites, in sufficient number to constitute a comprehensive physical survey of all forest types. Having permanent records as a framework, it is possible to tie in the measurements at temporary stations in such a way as to furnish good comparative data for local use.

In all climatic records for short periods the data are to be regarded as relative rather than absolute. Relative data are valuable if referred to a reliable standard. More representative records for a locality can be obtained by operating several stations on different sites during a short period than by operating a single station over a longer period.

Thermograph records at five or six stations during one growing season, if referred to a satisfactory control station, should give a fairly good indication of air temperature for a silvicultural unit comprising a single forest type in one locality. The usefulness of such records can be greatly increased by giving due attention to extremes and by employing suitable summation methods.

Soil-temperature readings have great possibilities not only as a measure of soil temperature but also as an index of solar radiation as influenced by cutting. That marked differences in soil temperature prevail under different degrees of crown cover is well illustrated by Table 12, which gives the average soil temperatures at a depth of 1 foot at three stations in the western yellow pine forest. During the months from June to September, 1918, station 1B on the north side of a group of tall trees averaged 8.4° F. colder than station 1C in practically full sunlight, and 2.7° colder than station 1A in about 25 per cent shade. Somewhat smaller though still significant differences were found during the same period in 1919, a year of exceptionally heavy rainfall. It is reasonable to assume that plants in different degrees of shade would receive different amounts of heat in approximately the same proportion as the soil. This assumption is borne out by the measurements of leaf temperature cited in the discussion of light requirements.

Although several methods of measuring light intensity are available, each has its disadvantages, and none seem fully to meet the needs of the forester. In general it may be said that the methods which promise to be in some measure adequate are too complex for field use. As has already been pointed out, the form of radiant energy which constitutes the critical factor varies with other conditions. It is surmised that under the conditions prevailing in the Southwest deficient light is to a large extent deficient heat. Soil temperature affords a rough measure of the heating effect of sunlight, and more accurate methods are available if required. It can not be assumed, however, that the measurement of heat energy alone or of any other single form of energy will reveal all that the forester needs to know about light.

Moisture, like temperature, is susceptible of determination on a relative basis by short-period observations. Because of the erratic distribution of precipitation, however, at least two full years' records are needed in each locality, and the stations should not be more than 2 miles apart. The records should be correlated with one and preferably more long-period stations in the same forest zone and locality. Measurements of precipitation should be supplemented by measurements of evaporation, humidity, and soil moisture. Soil examinations, with special reference to depth, physical characteristics, and organic matter, are indispensable in evaluating moisture records.

POSSIBILITIES IN THE USE OF PLANT INDICATORS

Plant indicators can probably be used advantageously to supplement instrumental records. The principle of the plant-indicator method is that plants having the same requirements should grow on the same sites. The presence of one or more members of a group associated on a given site might lead one to expect that others would also find congenial conditions here. This, however, does not always follow, unless their entire range of requirements is the same. When two species are growing side by side, it may be that temperature, for instance, is near the optimum for one and near the minimum for the other. Thus a slight decline in temperature that would not seriously affect the former species might eliminate the latter.

If definite relationships could be established between the requirements of trees and those of common herbs and shrubs, the lower vegetation could often serve as site indicators for certain tree species. Cajander (*9*) has employed this principle in working out the distribution of forest types or sites in Finland where the original forest has been destroyed or changed by artificial forces. In fully stocked stands, he has found a definite relation between rate of growth of trees and the composition of the ground vegetation, and he regards the latter as superior to height growth of the trees as an index of site quality. Preliminary work in the San Francisco Mountains, however, indicates that the problem is not so simple as might be supposed. The herbs which at first thought seem most characteristic of a forest zone are found to have a much wider range than the trees. Thus, the most common grasses of the western yellow pine zone, namely *Festuca arizonica* and *Muhlenbergia montana*, occur in all forest zones above the woodland almost up to timber line. Most of the smaller plants range through at least two forest zones. The possibilities of using such plants as indicators are strengthened by considering development as well as mere occurrence of species. *Festuca arizonica*, for instance, grows 2 or 3 feet tall in the western yellow pine zone, but in the Engelmann spruce zone it is seldom more than 1 foot tall.

Indicators may be negative as well as positive. For example, *Bouteloua gracilis*, which thrives best in the woodland or lower zones, occurs sparingly or is poorly developed on typical western yellow pine sites. From this it may be deduced, and experience in Arizona and New Mexico generally substantiates this conclusion, that areas on which *B. gracilis* attains normal development are not good western yellow pine sites. Generally speaking, the indicator method appears more promising as a means of estimating site quality than of predicting the possible range of trees.

A SCIENTIFIC BASIS FOR SILVICULTURE

Because of the fact that nature has already fitted the species to the sites one is likely to think of the application of a knowledge of forest types mainly in connection with the forestation of denuded or naturally treeless areas. This, however, is but one phase, and at present a minor one. The greatest need for definite data on the requirements of species is in the control of cutting. In marking timber for removal, the forester is continually speculating on the probable effect upon reproduction and upon growth of the remaining trees. But too often he thinks of the method of cutting or silvicultural system as acting directly instead of through its effect on basic physical conditions. Silvicultural studies by observation of what has taken place in old cuttings or by records on sample plots comprising various densities of cover are valuable but inadequate. Even if definite conclusions are reached, in the course of 15 or 20 years it will be found that they hold only for sites similar to those on which the study was conducted. A certain percentage of crown cover on a south exposure will probably give very different results from those obtained with the same cover on a north, east, or west aspect. The result will also vary with altitude. If investigations of this sort were supplemented by instrumental records it would be found that reproduction of various species is more directly related to heat, light, and moisture than to density of crown cover or silvicultural system.

Heat, light, and moisture are all to some extent susceptible of modification by silvicultural operations. Cutting increases the amount of sunlight which reaches the forest floor. The effect manifests itself far less in higher air temperatures than in an increase of heat available for direct absorption by the leaves of seedlings. If temperature conditions are already near the optimum this change may not be important, but if they are near the minimum it should prove highly beneficial. Whether photosynthesis is increased similarly depends on whether or not the light intensity before cutting was adequate for this activity. In this connection, the possible benefits from increased radiation of the short wave lengths should not be overlooked. In general, cutting brings about a temporary lowering of water consumption by eliminating the root action of the trees which are felled; but on spots exposed to the sun, the surface soil to a depth of 2 or 3 inches dries more rapidly because of increased evaporation.

Accurate measurements of the effects of silvicultural operations upon physical factors involve much painstaking work, but relatively simple measurements and observations may suffice to indicate general trends. The mere fact that a greatly enlarged soil area is exposed to the sun by cutting suggests substantial increases in the amount of heat available for seedlings. This can readily be verified by a few measurements of soil temperature in sunny and shaded situations. Changes in soil moisture can be detected by comparing soil samples from near the stumps of felled trees with samples taken near standing trees. Differences in wind and evaporation become apparent after only a few days' records in a cut-over stand and a neighboring virgin stand, or in several stands representing different degrees of cutting. Since air temperature is affected but little by cutting, definite changes can be detected only by means of rather long records.

EXAMPLES IN SILVICULTURAL PRACTICE

Some applications of data on the requirements of species in silvicultural practice may be illustrated by the following examples:

Western Yellow Pine Type

In the lower portion of the western yellow pine zone, moisture is the dominating factor in natural reproduction of western yellow pine. Seedlings often grow almost under the crowns of older trees, despite shade and root competition. Apparently this is because the shade favors germination by conserving surface soil moisture, and the air is warm enough to enable seedlings to grow with a small amount of direct sunlight. That heat is not deficient in such situations is indicated by the fact that soil temperature at the depth of 1 foot is about the same as in sunny situations in middle altitudes of the zone. Empirical silvicultural methods developed under such conditions would properly stress the importance of protection, with little thought of heat requirements. Such methods applied in the middle or upper part of the zone, however, would not give the best results. Records of air temperature supplemented by measurements of soil temperature in the sun and shade would show that heat conditions here are approaching the minimum and that reproduction is not to be expected in shaded situations.

Douglas Fir Type

In mixed stands of Douglas fir, white fir, western yellow pine, and limber pine, deficient surface moisture, caused by high insolation and attendant evaporation stresses, is the critical factor with the two first-named species, whereas it is deficient heat which limits western yellow pine. Limber pine tends to occupy an intermediate position, though it is more adaptable to opposite extremes than any of the other species. In stands of this composition it is usually considered desirable to favor Douglas fir and western yellow pine because of their greater commercial value. Silviculturally the balance is very delicate, and the forester's judgment will need to be checked by all the quantitative data available.

It will probably be found that where the mean maximum temperature for the summer months of June–September is below 72° F., western yellow pine seedlings will not thrive in shaded situations. In such places the soil temperature at a depth of 1 foot is likely to be below 57°. These and lower temperatures, however, are congenial to the other species, which will therefore gain the upper hand over western yellow pine, if the latter can survive at all. It will often be a question whether western yellow pine can reproduce to any appreciable extent even under heavy cutting, because of the shade cast by logging débris and undergrowth. If the aim is to get western yellow pine in the openings, the slash should be burned; if Douglas fir is preferred, enough slash should be left to provide moderate shade, but a deep accumulation of litter, which interferes with the early establishment of this species more than with white fir and limber pine, should be avoided. Near the upper limits of the Douglas fir zone, Engelmann spruce and corkbark fir are likely to take possession of the most heavily shaded spots. Here western yellow pine is eliminated by its high heat requirements, and Douglas fir is able to reproduce only in the lightly shaded or open situations. In many places, however, it is barred from sites exposed to full sunlight and wind. Where the mean maximum temperature from June to September is as low as 66°, Douglas fir, and to less extent white fir, is likely to be supplanted by corkbark fir and Engelmann spruce in shaded situations.

Engelmann Spruce Type

In the Engelmann spruce zone, as in the western yellow pine and Douglas fir zones, one sees a reversal of temperature and moisture relations in passing from the lower to the upper altitudes. In the transition from the Douglas fir to the Engelmann spruce zone corkbark fir and Engelmann spruce increase their domination on the cooler sites, and Douglas fir, white fir, and limber pine cling to the more sunny openings. Higher, first Douglas fir and then white fir disappear, but limber pine persists somewhat farther on the open south exposures, where it is joined by bristlecone pine. Toward the upper limit of the zone, corkbark fir begins to drop out. It does not reproduce well in shaded situations where the summer soil temperature falls below 48° F. Bristlecone pine persists to the upper limits of tree growth on ridges and south exposures. Engelmann spruce alone marks the true low-temperature timber line on north exposures. There the summer (June-September) mean maximum temperature is about 55°, and that of the soil in the open at a depth of 1 foot is about 44°. The trees are erect but low growing, and for several hundred feet below timber line there is a marked absence of reproduction. Apparently the present stand started in the open, perhaps after a fire, and now it is only where relatively large breaks occur in the canopy that reproduction takes place. Thus spruce, which apparently surpasses all other species in this region in its ability to function in low temperature, reaches its final limit, and, as in other species, this limit makes its first appearance among the seedlings that are deprived of a large proportion of the insolation which larger trees are able to appropriate by virtue of their more commanding position.

THE STUDY OF TIMBER-SALE AREAS

Cutting as a means of regulating heat, light, and moisture conditions and thus controlling the composition of the future forest is an effective implement in the hands of the silviculturist. But, without adequate knowledge regarding its proper use, it can become a dangerous implement. It is doubtful whether the problem of cutting can be fully solved by methods of trial and error, which include sample-plot records. In addition to all that can be determined by observation and deduction we need quantitative standards and a measuring stick for determining the kind and amount of change required to bring about the desired results. In timber sales, volume estimates are checked by actual measurements and the minimum selling price is determined by formula. But when it comes to determining proper silvicultural practice to insure restocking and growth, we have no quantitative standards against which the judgment of the forester can be checked. Along with the timber estimates, stumpage appraisal, and logging plans which precede timber sales, there should be an adequate silvicultural study of the proposed cutting area. An important feature of this study should be the best possible appraisal of site factors.

SUMMARY

Seven broad zones of climate and vegetation, determined largely by altitude, are recognized in Arizona and New Mexico. The vertical order, beginning with the lowest, is desert, grassland (including chaparral), woodland, western yellow pine zone, Douglas fir zone, Engelmann spruce zone, and alpine sedge land.

Air temperature generally falls with a rise in altitude. This relation is much more consistent with respect to the maxima than the minima.

Soil temperature also declines with a rise in elevation, in a general way following the course of average air temperature. Aspect, steepness of slope, ground cover, and depth all have an important bearing on soil temperature.

Precipitation, except for local variations, increases directly with altitude. Up to about 9,000 feet in the San Francisco Mountains the increase is rapid and consistent; beyond this altitude there is still an increase, but the rate falls off.

Wind movement apparently increases with altitude, but the relation is to a large extent obscured by forest cover.

Evaporation is increased by wind and also by temperature and low atmospheric humidity. The highest rate of evaporation is recorded on the desert. In the San Francisco Mountains the highest rate was found on an open southwest slope at an altitude of 10,000 feet.

Soil moisture is generally much more abundant in the Douglas fir and Engelmann spruce zones than in the lower vegetational zones.

Soil differences within this region apparently are due more to physical than to chemical characteristics. Other things being equal, the more porous soils are best suited to tree growth.

The natural occurrence of species coincides very closely with the areas meeting their heat and water requirements. It is not considered practical, by planting or otherwise, to extend the permanent range of a species appreciably beyond the range within which the individuals of that species occur or have occurred in the past.

The upper altitudinal range of a species is determined by its ability to function in low temperature, and the low range is determined by its ability to resist drought. In both cases it is the minimum which imposes prohibitive conditions. Except in rare instances where drainage is poor, moisture never becomes excessive for any species in the Southwest. It is possible that the high temperatures of the lower desert may be excessive for some species, but the evidence at hand indicates that all forest trees in this region could descend several thousand feet below their present range if adequate moisture were available.

There appears to be but little difference in the ability of species to extract moisture from dry soil; that is, they all reduce it to the wilting point which in a given soil is about the same for all species. Probably the greatest difference between species lies in their ability to extend their roots and thus enlarge the sphere of their activity. Experiments with blue spruce, Douglas fir, western yellow pine, and limber pine have shown that when the soil moisture approaches the wilting coefficient all reduce transpiration to practically nothing, and that they are able to persist in this state for months at a time.

Because of the fact that temperature decreases while moisture increases with a rise in elevation, the maximum of one factor coincides with the minimum of the other. Therefore, a species which has high temperature requirements must be able to grow with relatively little moisture, and one which has high moisture requirements must be able to grow in low temperature.

Winterkilling and unseasonable frost, though probably responsible for eliminating certain species from certain sites, are not thought to be of general importance as limiting factors in the distribution of species.

Where the temperature is too low for a given species to function normally, the deficiency of heat appears to manifest itself in low maxima rather than in low minima. For this reason the mean maximum is considered a better index than the mean, and growing-season temperatures are more significant than those for the whole year.

Soil rarely acts as a limiting factor in this region except in a local way and in conjunction with climatic limitations. The most important effect of variations in soil is to increase or decrease the amount of moisture available for plant growth. Without ignoring chemical composition and geologic origin, it is probably safe to say that the soil properties with which foresters are mainly concerned in this region are depth, physical composition, and organic content.

Light is not regarded as a limiting factor in the range of trees, but it may have an important bearing on the composition of stands. In the Southwest, where species must occupy zones of low temperature in order to satisfy their moisture requirements, demand for direct insolation is likely to be more a matter of heat than of light for photosynthesis.

It is reasonable to expect that silviculture can be improved by making use of exact quantitative data on temperature, moisture, and soil with reference to the requirements of species and the characteristics of forest zones and sites. This class of data would supplement and refine rather than supplant existing methods. The figures here presented are usable within the limitations which have been indicated.

APPENDIX

METHODS OF STUDY EMPLOYED IN COMPILING SAN FRANCISCO MOUNTAINS RECORDS

AIR TEMPERATURE

Thermographs were checked by maximum and minimum thermometers, exposed in shelters 5 to 7 feet above the ground, or well above ordinary snow depth. At cooperative Weather Bureau stations, the floors of the shelters are usually 4 feet above the ground, and the thermometers are fastened 18 inches above the floor. Experiments carried on during June and July, 1914, in the western yellow pine type showed that thermometers placed at 5½ feet gave minimum temperatures averaging 2.1° lower and maximum temperatures 0.6° higher than those exposed at 8 feet.

The shelters used in this study were all of the standard Weather Bureau type, with the exception of those at timber line, which were wooden boxes constructed with special consideration for ventilation and shelter of instruments against direct exposure to the sun. At the western yellow pine station, the thermographs were checked daily; at the other stations once a week.

When thermographs are in good running order the errors are usually too small to require correction.

Where readings are made only at long intervals, however, it is by no means certain that the error indicated by maximum and minimum thermometers applies to the extremes for each day; in fact, it rarely does. Whether or not it applies must be determined from the relation between errors in the maximum and minimum and from current checks. If, for instance, the errors appear to be due to too great an amplitude in the pen arm, as is the case when the graph is high on the maximum and low on the minimum, these must be scaled down for the more moderate extremes. If, on the other hand, the readings indicate a constant error, due to the pen arm being set too high or too low, a uniform correction should be applied.

SOIL TEMPERATURE

The temperature of the soil was in most cases measured by means of a thermometer suspended in a wooden tube to a depth of 6 inches, or in a ¾-inch metal pipe to depths of 1 and 2 feet. Several wood-encased soil thermometers were used, but they are expensive and have several other disadvantages. During periods of freezing and thawing they tend to heave out of the ground; they are easily broken in replacing; in deep snow, they can be read only with extreme difficulty. Where pipes or tubes are used under such conditions they are allowed to extend 6 inches or a foot above the ground, and the thermometers are taken out for reading, the bulbs being covered with cotton or imbedded in cork to prevent sudden changes. When pipes are exposed to the sun they are wrapped with burlap. With this protection, the errors due to conduction by the metal are negligible.

Tests with thermographs have shown that at depths of 12 to 24 inches, the diurnal fluctuations are too small to require taking into account the difference of two or three hours in the time of observation. Readings at intervals of a week obviously do not give a complete record of the temperature movement, but they are thought to furnish a fair basis for comparison between various stations. Soil thermographs checked by thermometers were used for all records at depths of 6 inches or less.

PRECIPITATION

Rainfall was measured by means of standard 8-inch rain gauges. Snowfall was converted into water equivalent by melting or by weighing. At the mountain stations it was difficult to obtain an accurate catch for a single storm or for a given period. When the stations can be visited only at intervals of a week or more, this problem is a serious one. Because of drifting, which often completely covers a gauge during a single storm, the catch obtained from an open can is unreliable. Drifting is rare in dense stands of timber, but here a very large proportion of the snow is usually retained by the crowns and blows off several days after the storm, or melts and falls in large masses. All things considered, the most accurate method of measuring winter precipitation in the mountains is to take average samples of the snow on the ground at intervals of a month or less through the winter. Using figures obtained in Utah in 1917 as an index, the total winter evaporation of snow in the Douglas fir and Engelmann spruce types probably amounts to between 2 and 3 inches of water. The loss by melting and run-off is negligible because what little water is formed by melting on the surface is absorbed by the deep mass of snow underneath. Repeated examinations have shown that the ground underneath the snow remains frozen and contains no excess of surface water until the beginning of spring thaws.

The total snowfall for the winter was measured in two ways. One was to leave the overflow can of a rain gauge out all winter. It became filled with snow and was covered to a depth of 2 or 3 feet. As melting proceeded in the spring, the snow settled down until a fairly representative core was contained within the gauge before any appreciable amount of free water was formed. In some instances the gauge burst, but in others it held. The other method employed a snow sampler by means of which an average core of snow as it lay on the ground was extracted and weighed. Two instruments were used—one described by Church (*9a*) and the other by Kadel (*21a*). Both gave essentially the same results; direct comparisons usually agreed within 10 per cent. The average of such results, or the determinations made by the snow sampler alone, have been accepted as giving the best available record of winter precipitation.

EVAPORATION

Evaporation was measured by weekly measurement of the water level in a circular galvanized-iron tank 15 inches in diameter and 8 inches deep placed on the ground in a level position. Measurements were made to the nearest tenth of an inch by means of a rain-gauge stick. At each reading, water was added in sufficient amount to raise the level to 4 inches. A rain gauge placed a few feet distant made it possible to make allowance for rainfall. A screen of ½-inch mesh served to exclude animals and coarse litter, a precaution which experience had proved necessary.

It is recognized that this method is crude, but after considering various methods, it was adopted as the most practical and reliable. The porous cup atmometer is not well adapted to this region because of the prevalence of freezing night temperatures through May and June which is the critical period from the standpoint of evaporation. The Piche evaporimeter is subject to the same limitations. At the time this study was initiated, the Bates inner-cell evaporimeter was in the developmental stage. In its present form this instrument would probably be the most satisfactory available. Greater refinement in the method of measuring the water level in the tanks would have been possible had any of the several improved devices now in common use been employed, but it was felt that in view of the long interval between readings such refinement would be inconsistent with the general standard of accuracy attainable under the conditions encountered in this study.

WIND

Standard United States Weather Bureau anemometers were used for recording velocity. For various reasons no serious attempt was made to maintain continuous records at all the stations. Owing to the fact that the anemometer provides no means of indicating the number of complete revolutions on the dial, the movement in open, windy situations, during a period as long as a week, is usually more or less uncertain. It would no doubt have been possible to improvise a reliable recording device had this been considered of great importance. Instead, check readings were made at 1 or 2 day intervals during limited periods. In all cases, the anemometers were placed at a height of 8 feet above the ground.

HUMIDITY

Psychrometer readings were taken at the control station daily at about 8 a. m. and three times daily during limited periods. The only other daily readings were in the Douglas fir zone on Mount Graham. These were compared with simultaneous readings in the town of Safford, some 6,000 feet below. Two hygrographs were tried out at the control station, but they proved too erratic to be relied upon for the mountain stations with infrequent checks.

SOIL MOISTURE

Samples were obtained by digging to the desired depth with pick and shovel. The stony character of the soil generally encountered in this region precludes the general use of soil augers or soil tubes. Moreover, the method employed, though laborious, rendered it possible to obtain more representative samples than can be had by means of an auger or tube. The practice followed was to dig a hole to the depth of the lowest sample desired. Samples were then taken from two or more walls with a trowel. The outside layer was always removed so as to avoid any effects of drying. Samples were obtained at the following levels: Surface, 1 to 2 inches, 6 inches, 12 inches, and 24 inches. An effort was made to get the samples at these depths rather than a core from 0 to 6 inches, 6 to 12 inches, etc. Each depth was represented by samples from two holes.

The interval between taking samples was usually one month. In normal years, at least, this interval is regarded as sufficiently short, because of the well-defined seasons of drought and rainfall in this region. In the spring of the year the soil is almost invariably saturated from the preceding winter's snow. Drying proceeds gradually, sometimes being interrupted by rain or snow in April and May but rarely in June. June or early July is always the critical period. For this reason it is desirable to obtain a series of samples about the middle of June and again just before the summer rains, which usually begin between July 1 and July 15. Samples in July and August show the penetration of the summer rains, and samples in September and October indicate the severity of the autumnal drought. The usual trend of the moisture graph for depths below 6 inches in this region is as follows: High in April and May, the seasonal minimum about July 1, high in August, and a rather gradual decline in September and October. During the 15 years in which more or less complete records have been kept at the Southwestern Forest and Range Experiment Station, 1919 with its great excess of rainfall is the only year which shows an appreciable departure from the usual. Although a much shorter interval between measurements would be desirable for surface sampling, a good indication of surface moisture is furnished by rainfall and evaporation records.

In order that samples taken at different times and at different stations may be comparable, it is important to give careful attention to the effect of growing vegetation. All samples for each station were taken from sampling spots located in zones of apparently average root activity or, for certain purposes, from two sampling spots, one near the trees and another as far as possible beyond their influence.

The fact that the soils in this region contain greatly varying proportions of gravel and stones caused a perplexing problem to arise. A test in 1919 showed that the coarse material removed from several samples by sifting through a screen of 10 meshes to the inch contained appreciably less moisture than the finer material. In order to insure approximate uniformity in regard to the amount of coarse material present, all samples were run through a screen of 10 meshes to the inch. A finer screen was found unpractical because it became clogged by sticky soils.

WILTING COEFFICIENT

The wax-seal method of Briggs and Shantz was employed. Despite the criticisms of this method, it is thought to express in a fairly satisfactory way the relation between the plant and its available moisture supply. Caldwell has found that the amount of moisture left in the soil at permanent wilting varies greatly with environmental conditions, but that it is greatest when the rate of transpiration is high. It is obvious that plants exposed to a hot, dry atmosphere in bright sunlight will wilt with a higher soil-moisture content than if they are exposed to cool, moist air and are shaded. During protracted periods of cloudy weather, the process of wilting is exceedingly slow. Even in the clear, dry weather of June and September in the Southwest, permanent wilting is a matter of several days. Plants which wilt in the afternoon sun usually revive at night. After this process has been repeated on three or four successive days, the plants often recuperate when placed in a moist chamber. Moreover, when several individuals of the same species are grown in the same pot some remain fresh after their companions are completely wilted.

From the foregoing, it is evident that wilting is not the result of the conditions prevailing at a given moment or hour, but rather the cumulative effect of varying conditions during several days. It is true that after a plant has approached very near a state of permanent wilting, death may be either hastened or postponed by the atmospheric conditions of a single hour. But transpiration tests with conifers have shown that after the seedlings reach this stage the water loss during an additional day is so small that it will affect the wilting coefficient by less than a tenth of 1 per cent. Greater refinement than this is without meaning.

Oat seedlings were grown in tumblers in an unheated greenhouse. Two or sometimes three tumblers of the same soil were tested side by side. As a rule the individual variation was less than 0.3 per cent. Where it exceeds this figure the results are considered unsatisfactory though not necessarily without value. To those who are accustomed to seeing wilting coefficients carried out to the nearest hundredth of a per cent, the standards described may appear crude. On the other hand, when the many possible sources of discrepancy—the individual variation of plants, the variability of the soils used in the test, and, finally, the probability that the soils on which the tests are made are not truly representative of the series of moisture samples taken through a season—are considered, it would indeed seem remarkable if the experimental error under field conditions proved to be less than 0.3 per cent.

DESCRIPTION OF CLIMATOLOGICAL STATIONS EMPLOYED IN THE SAN FRANCISCO MOUNTAINS STUDY

STATION 1A.—WESTERN YELLOW PINE TYPE, CONTROL STATION

Location.—Fort Valley Branch Station one-fourth of a mile north of station buildings, 9 miles northwest of Fagstaff, Ariz.

Situation.—In the forest one-fourth of a mile northwest from the nearest edge of an open valley 1 to 1½ miles in diameter on a gentle south slope about 40 feet above the floor of the valley. Altitude, 7,300 feet. The station is at the foot of the San Francisco Mountains from which there is a strong flow of cold air at night. The immediate site is in an opening about 100 feet in diameter. Groups of large trees stand to the east, south, and west of the instruments at distances of from 40 to 75 feet. Single trees occur some 60 to 75 feet north and large groups a little farther back.

Forest cover.—Virgin stand of western yellow pine of optimum development for this region, dominants 100 to 115 feet tall.

Ground cover.—Open bunch grass; litter of pine needles.

Soil.—Reddish stony clay loam derived from basalt, clay subsoil; depth 3 to 4 feet.

Instruments.—Air and soil thermograph, maximum and minimum thermometers, soil thermometers, psychrometer, anemometer, evaporation pan, and rain gage. Air thermometers and anemometer placed 8 feet above the ground.

Period of records.—Continuous since 1908, except soil temperatures which began in 1915.

STATION 1B.—WESTERN YELLOW PINE TYPE (SHADE SUBSTATION)

Located 40 feet southwest of station 1A, on the northeast side of a large group of tall trees, shaded after 11 a. m.; pine litter 1 to 2 inches deep; sparse cover of broad-leaved herbs; records of soil temperature 1916 to 1920.

STATION 1C.—WESTERN YELLOW PINE TYPE (SUN SUBSTATION)

Located 60 feet northwest of 1A; receives full sunlight between 9 a. m. and 5 p. m. in summer; soil and ground vegetation the same as at 1A except more grass and a few pine seedlings; records of soil temperature and surface air temperature (shelters placed 4 inches above ground) 1918 to 1919.

STATION 3.—WOODLAND, UTAH JUNIPER

Location.—Ash Fork ranger station, about 1 mile northeast of Ash Fork, Ariz.

Situation.—North side of a large open valley; instruments on a gentle south slope about 25 feet above the floor of the valley. Altitude, 5,100 feet.

Forest cover.—Open stand of Utah juniper; no piñon occurs here.

Ground cover.—Sparse cover of short grass.

Soil.—Reddish stony clay of volcanic origin.

Instruments.—Maximum and minimum thermometers and rain gage permanent equipment; thermograph, 1-foot soil thermometer and evaporation pan temporary. Air thermometers 5 feet above ground.

Period of records.—Air temperature and precipitation 1917 to 1926; soil temperature and evaporation during summer and fall of 1918.

STATION 4.—WOODLAND, PIÑON—JUNIPER

Location.—About 2 miles east of Walnut Canyon ranger station, 11 miles southeast of Flagstaff.

Situation.—On nearly level ground about 75 yards south and 25 feet above the road. Narrow, sparsely wooded valley, 50 yards east. Altitude, 6,500 feet.

Forest cover.—Dense stand of piñon, one-seed, and Utah juniper. Instruments in a natural opening about 30 feet in diameter.

Ground cover.—Short grasses and scattered shrubs.

Soil.—Shallow very stony loam derived from limestone.

Instruments.—Air thermograph, maximum and minimum thermometers, and rain gage. Thermometers 4 to 5 feet above the ground.

Period of records.—Summer, 1918.

STATION 5.—WESTERN YELLOW PINE—WOODLAND TRANSITION

Location.—Walnut Canyon ranger station, 9 miles southeast of Flagstaff.

Situation.—Nearly level, gentle easterly slope, 50 yards from a deep canyon. Altitude, 6,700 feet.

Forest cover.—Open stand of western yellow pine, piñon, and junipers. Instruments not shaded appreciably.

Ground cover.—Short grass and scattered shrubs.

Soil.—Rather light sandy loam derived from sandstone and limestone.

Instruments.—Maximum and minimum thermometers and rain gage permanent equipment; soil thermometer and evaporation pan temporary; air thermometers 5 feet above the ground.

Period of records.—Air temperature and precipitation about eight months of the year since 1914; soil temperature and evaporation during the summer of 1918.

STATION 6.—WESTERN YELLOW PINE TYPE

Location.—Williams, Ariz.

Situation.—Forest supervisor's office, near the middle of town, north hillside about 100 feet above the floor of an open valley to the north and east. Bill Williams Mountain, 9,500 feet high, is about 5 miles south. Altitude, 6,750 feet.

Forest cover.—The original stand of western yellow pine has been cut in the immediate vicinity. Natural young growth of pine and juniper occurs within a half mile to the south and west, and occasional trees remain in the south part of town near where the instruments are located.

Instruments.—Maximum and minimum thermometers and rain gage. Air thermometers 5 feet above ground.

Period of records.—Continuous since 1907.

STATION 7.—WESTERN YELLOW PINE TYPE

Location.—Flagstaff, Ariz.

Situation.—The instruments have been moved several times. They are now in the north part of town on the south brow of a hill about 50 feet above the lower districts. The whole town, however, is in a valley which receives considerable cold air drainage from the San Francisco Mountains 12 miles to the northwest. Altitude, 6,900 feet.

Forest cover.—The town is surrounded by a western yellow pine forest, mostly cut over. Occasional trees remain in various parts of town.
Instruments.—Thermograph, maximum and minimum thermometers, psychrometer, and anemometer. Air thermometers 11 feet above the ground.
Period of records.—Continuous since 1897 (United States Weather Bureau).

STATION 8A.—DOUGLAS FIR TYPE

Location.—Lower slopes of San Francisco Mountains almost on a direct line between the experiment station and the tip of Mount Agassiz.
Situation.—Steep northwest slope, about 75 feet above the bottom of a narrow treeless valley 100 yards to the west. Altitude, 8,900 feet.
Forest cover.—Mixed stand of Douglas fir, corkbark fir, and limber pine. Instruments in a natural opening 40 by 70 feet in diameter, shade at air and soil thermometers about 60 per cent.
Ground cover.—Sparse cover of low herbs.
Soil.—Light sandy loam of good depth but mixed with stones and large bowlders, belonging to the acidic volcanic group. Abundant organic matter in surface 2 to 3 inches.
Instruments.—Maximum and minimum thermometers, air and soil thermographs, soil thermometers, rain gage, and evaporation pan. Air thermometers 8 feet above the ground.
Period of records.—Continuous from 1917 to 1919, inclusive.

STATION 8B.—DOUGLAS FIR TYPE (ASPEN)

Location.—About 100 feet east of station 8A.
Situation.—On a nearly level bench slightly higher than 8A.
Forest cover.—Aspen with scattered young conifers.
Ground cover.—Dense growth of low herbs, such as fern and vetch.
Soil.—Similar to that on 8A but less rocky.
Instruments.—Soil thermometer, rain gage, and evaporation pan.
Period of records.—1918 and 1919.

STATION 8C.—DOUGLAS FIR TYPE, OPEN—UPPER LIMIT OF WESTERN YELLOW PINE

Location.—About 100 yards below 8B.
Situation.—In a narrow opening on a steep south slope.
Forest cover.—One of the last outposts of western yellow pine, apparently marking the upper limit of the species. A lone tree about 40 feet tall occurs here. No western yellow pine seedlings are found in the vicinity, and very few cones are in evidence. Aspen thickets occur at a distance of about 100 feet on the east and west sides.
Ground cover.—Short grass.
Soil.—Similar to 8A but less rocky.
Instruments.—Soil thermometer at a depth of 1 foot.
Period of records.—1919.

STATION 9.—LIMBER PINE—BRISTLECONE PINE

Location.—About 1 mile up the slope from the Douglas fir station.
Situation.—On a steep, bare southwest slope. Altitude, 10,000 feet.
Forest cover.—Scattered specimens of limber pine and bristlecone pine, too far apart to afford shade or wind protection.
Ground cover.—Mixed grasses and occasional bushes.
Soil.—Very light gravelly loam derived from acidic volcanic rocks. Large bowlders appear on the surface here and there.
Instruments.—Maximum and minimum thermometers, thermograph, soil thermometers, rain gauge, evaporation pan, and anemometer. Air thermometers 6 to 7 feet, anemometer 8 feet, above the ground.
Period of records.—1918 and 1919.

STATION 10A.—ENGELMANN SPRUCE TYPE, NORTHWEST SLOPE

Location.—On the west shoulder of Mount Agassiz as seen from the experiment station, about 1 mile above the limber pine–bristlecone pine station.
Situation.—On a steep northwest slope about 100 feet below the top of a long ridge leading directly to the top of Mount Agassiz. Below is a deep canyon. Altitude of station, 10,500 feet.

Forest cover.—Dense stand of mature Engelmann spruce and corkbark fir. Shade about 90 per cent. Instruments in a natural opening about 15 feet in diameter.

Ground cover.—Practically no vegetation occurs under the densest cover. In openings are young spruce and fir, low shrubs, and herbs. Snow lies here until the end of June.

Soil.—Deep sandy loam, mixed with stones and large rocks, many of which appear on the surface. The rocks which are of the acidic type are distinctly granular in contrast to the fine-grained basalt predominating in the western yellow pine type. A leaf litter 1 to 3 inches deep covers the ground, and the upper 2 to 3 inches of soil contains a large amount of organic matter.

Instruments.—Maximum and minimum thermometers, air thermograph, soil thermometers, anemometer, rain gauge, and evaporation pan. Air thermometers 8 feet above the ground; rain gauge and evaporation pan in a near-by opening about 40 feet in diameter.

Period of records.—Continuous 1917 to 1919, inclusive.

STATION 10B.—ENGELMANN SPRUCE TYPE, RIDGE

Location.—Near station 10A.

Situation.—On a ridge about 100 feet above 10A, gentle southwest slope. Altitude 10,500 feet.

Forest cover.—The instruments are in natural opening 90 to 100 feet in diameter, surrounded by dense stands of Engelmann spruce and corkbark fir. The spruce here is generally shorter than at station 10A.

Ground cover.—Open growth of herbaceous plants such as Aquilegia, Dougaldia, Bromus, and Carex. The leaf litter is thinner than on the north slope.

Soil.—About the same as at station 10A, except less undecomposed organic matter.

Instruments.—Maximum and minimum thermometers, air and soil thermographs, soil thermometers, rain gage and evaporation pan. Air thermometers 6 feet above the ground.

Period of records.—1918 and 1919.

STATION 11A.—TIMBER LINE, RIDGE

Location.—Up the ridge from stations 10A and 10B, toward the top of Mount Agassiz.

Situation.—On a ridge about 200 feet wide, steep west slope. Altitude, 11,500 feet.

Forest cover.—Engelmann spruce and bristlecone pine occur in large numbers, but they assume a bushy or prostrate form.

Ground cover.—Sparse growth of Ribes, Polemoneum, Carex, and grasses. In many places the soil apparently is too coarse to support vegetation.

Soil.—Derived from acidic volcanic rocks, mostly ryolite; there are pockets of good soil, but generally it is very coarse and there are large areas of gravel slide.

Instruments.—Maximum and minimum thermometers, air thermograph, soil thermometers, rain gage, evaporation pan, and anemometer (short periods). Air thermometers 7 feet, anemometer 8 feet above the ground.

Period of records.—1917 to 1919, inclusive. Except in 1917 it was often impossible to reach this station between December and April.

STATION 11B.—TIMBER LINE, NORTHWEST SLOPE

Situation.—Over the ridge on the northwest slope about 100 yards from 11A. Altitude, 11,500 feet.

Forest cover.—The station is at the upper edge of a pure stand of Engelmann spruce which here terminates abruptly. The trees are straight and 40 to 50 feet high. The bushy form characteristic of the ridge station is almost absent.

Ground cover.—A few prostrate spruces, Ribes, Polemonium, and Carex.

Soil.—Similar to that at station 11A, very rocky, bordering on a gravel slide.

Instruments.—Maximum and minimum thermometer, thermograph, soil thermometer, anemometer (short periods). Thermometer shelter 7 feet and anemometer 8 feet above ground.

Period of records.—Summer and fall of 1918 and 1919.

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